Aero

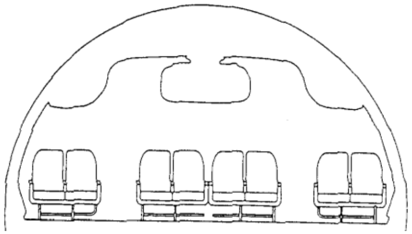
Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

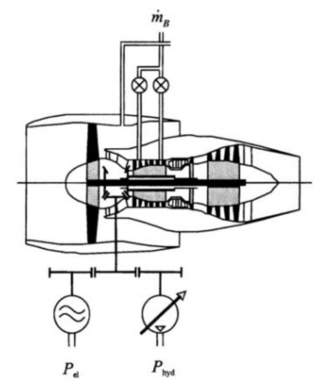
AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Cabin Air Contamination

– An Aeronautical Perspective

Dieter Scholz — Hamburg University of Applied Sciences





Deutscher Titel: "Kabinenluftkontamination aus technischer Sicht"

59. Kongress der Deutschen Gesellschaft für Pneumologie und Beatmungsmedizin e.V.

16.03.2018, Dresden, Germany

Structured Abstract

Purpose – This presentation gives an introduction to aircraft cabin air contamination with an emphasis on contamination due to jet engine oil entering the cabin from the jet engine or auxiliary power unit (APU) via the bleed air system and the air conditioning system. The possible application of sensors and filters is discussed. Filters can be retrofitted. A bleed-free air conditioning architecture, however, seems only financially viable for newly designed aircraft.

Design/methodology/approach – The presentation collects existing facts and combines them with own thoughts.

Findings – There is a real health and flight safety risk due to contaminated cabin air. For the infrequent flyer the risk is very low. Also aviation statistics are not dominated by cabin air related accidents. Nevertheless, a bleed air based air conditioning system can be regarded as applying a fundamentally wrong systems engineering approach. Measures have to be taken to solve this.

Research limitations/implications – This review study is based on references. Own measurements have not been made.

Practical implications – The topic has been presented as background information for respiratory physicians.

Originality/value – Engineering based information with a critical view on the topic seems to be missing in public. This presentation tries to fill this gap.

Any further request may be directed to Prof. Dr.-Ing. Dieter Scholz, MSME
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Introduction

MEDICAL INVESTIGATION DAVID LEARMOUNT LONDON

Cabin air killed BA pilot, say experts

Authority on organophosphate poisoning says tissue from Richard Westgate, who died in 2012, "worst case" he has seen

Sustained exposure to organophosphates (OP) from contaminated cabin air contributed to the death of a 43-year-old British Airways pilot, a group of medical experts believe.

Their findings are likely to increase pressure on the industry to take more seriously the issue of sustained exposure to engine bleed air. Airlines and governments have dismissed suggestions that it can be a factor behind flightcrew falling ill.

The pilot, senior first officer Richard Westgate, started flying professionally in 1996 and medical details of his symptoms before death are on record.

Although no coroner's inquest has been held into his death, medical experts led by Prof Mohamed Abou-Donia of Duke University Medical School, North Carolina, the world's leading authority on organophosphate poisoning, have just published a study into two autopsies carried out on Westgate, who until his illness was a slim, fit paragliding champion.

Abou-Donia and his colleagues are also investigating the death this year of an unnamed 34-year-old BA airline steward, whose

Westgate: series of symptoms

by far." He adds: "The air transport industry constantly over- cabin, but they – and aircraft manufacturers – maintain that this is at a harmless level. Abou-Donia argues this was not so in Westgate's case, despite the fact that the pilot had never logged an actual "fume event" during his career.

WATERSHED

Frank Cannon, the lawyer acting for the families of both deceased, says the Westgate case is a watershed in this controversy: "They can try explaining one [case] away, but not another and then another." Cannon says he has "about 50" cases on his books.

■ ■ ■

(Flight International 2014)

Introduction

... but ...

The Telegraph

By **Telegraph Reporters**

13 APRIL 2017 • 3:23PM

The family of a British Airways co-pilot who believed he had been poisoned by contaminated cockpit air have accused the airline industry of having its "head in the sand" over the issue.

Richard Westgate, 43, died in December 2012 after moving to the Netherlands to seek help from a specialist clinic for his symptoms which he thought were caused by "aerotoxic syndrome", which has been called "pilot's disease".

A coroner ruled Mr Westgate died accidentally at the Bastion Hotel in Bussum, Netherlands after taking an unintentional overdose of the sleeping tablet pentobarbital.

(Telegraph 2017)

A controversial issue!

Introduction

Definition: Aircraft Cabin Air

Aircraft cabin air is the air in the cabin of an aircraft. The air in the cockpit is included in this definition. In pressurized cabins it is the air inside the pressure seals. Pressure control is such that cabin pressure is reduced down to a pressure equivalent to 8000 ft (referring to the ICAO Standard Atmosphere) as the aircraft climbs. In unpressurized aircraft cabins the air is at ambient pressure. Temperature control is done by heating or cooling as required. Venting ensures frequent exchange of cabin air with fresh air from outside. In addition, cabin air can be recirculated and filtered. When flying at high altitudes, cabin air is at similar low relative humidity as the air outside.

Definition: Quality

Degree to which a set of inherent characteristics fulfills requirements.

(ISO 9001)

Introduction

Definition: Contamination

The process of making a material unclean or unsuited for its intended purpose, usually by the addition or attachment of undesirable foreign substances.

Adapted from (Wiktionary 2018)

The presence of a minor and unwanted constituent (contaminant). Related to health: A harmful intrusion of toxins or pathogens e.g. in food, water, or air.

Adapted from (Wikipedia 2018a)

Definition: Fume Event (Rauchereignis)

In a fume event, the cabin and/or cockpit of an aircraft is filled with fume. The fume originates from the bleed air and enters the cabin via the air conditioning system. Air contamination is due to fluids such as engine oil, hydraulic fluid or anti-icing fluid.

Adapted from (Wikipedia 2018b)

Introduction

Definition: **Smell Event** (Geruchsereignis)

A fume event without visible fume or smoke, but with a distinct smell usually described as "dirty socks" from the butyric acid originating from a decomposition of the esters that are the base stock of the synthetic jet engine oil.

Definition (ECA): **Smoke & Fume / Smell Event (cabin air contamination)**

An incident may cause only fume, only smell or both. The European Cockpit Association (ECA) explains: "In the context of the ICAO circular [ICAO Circular 344 'Guidelines on Education Training and Reporting Practices related to Fume Events'], fumes and odours are deemed to be synonymous, and the term 'fume(s)' includes both fumes and odours."

(ECA 2018)

Definition (IATA): **Cabin Air Quality Event (CAQE)**

"Cabin air quality events (CAQEs) [are] particularly ... the so-called fume events" (smoke, fumes / odours). (IATA 2018)

Proposed new Definition:

Definition: Cabin Air Contamination Event (CACE)

In a Cabin Air Contamination Event (CACE) the air in the cabin and/or cockpit of an aircraft is contaminated. Sensation of the contamination can be from vison (fume/smoke), olfaction (smell/odor), a combination of typical symptoms experienced by several passengers and/or or crew or by related measurements of CO, CO2, ozon or other "harmful or hazardous concentrations of gases or vapours" (CS-25.831).

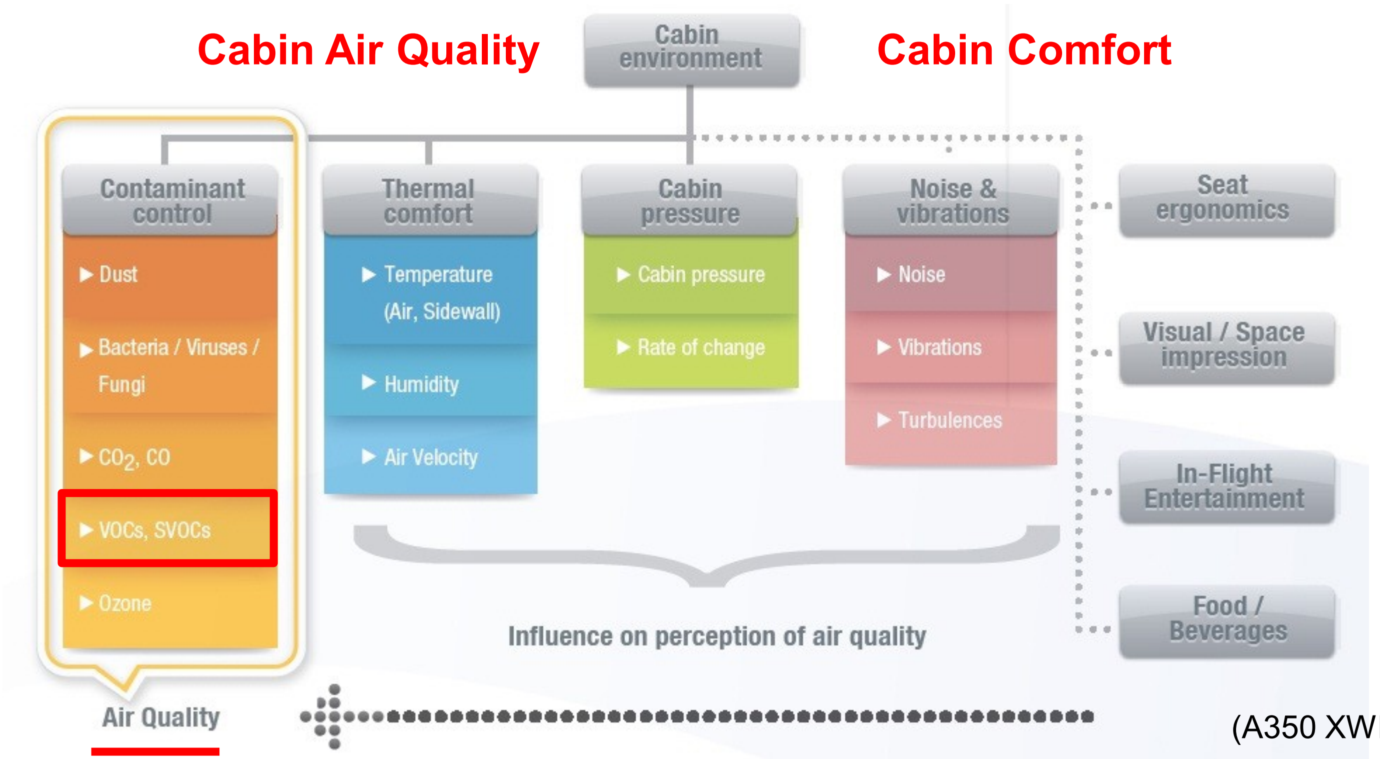
Headache	Drowsiness
Dizziness	Impaired vision
Nausea	Vomiting
Tingling (e.g. hands, feet, etc.)	Trembling
Numbness	Irritated eyes/throat/nose
Difficulty speaking and finding words	Memory problems
Muscle incoordination	
Breathing difficulties	Coughing

Typical Symptoms following a CACE (ECA 2017)

Cabin Comfort and Cabin Air Quality –

Health and Flight Safety Implications

Cabin Comfort and Cabin Air Quality – Health and Flight Safety Implications



(A350 XWB News 2012)

VOC: Volatile Organic Compounds are (organic chemicals – i.e. including carbon) contained in many products and can be released from these products into the surrounding air. **Regulations limit VOCs.**

SVOC: Semi-Volatile Organic Compound (Eurofins 2017)

Potential Concerns Related to Cabin Air Quality

• Cabin Pressure	Can effect people with cardio-respiratory diseases from lack of oxygen
• Relative Humidity	Temporary drying of skin, eyes, and mucous membranes
• Carbon Monoxide	High concentrations during air-quality incidents. Frequency is believed to be low. CS 25.831: Concentration must be lower than 50 ppm.
• Carbon Dioxide	Concentrations are generally below FAA regulatory limits. Associated with increased perceptions of poor air quality. CS 25.831: Concentration must be lower than 0.5%.
• Ozone	Elevated concentrations on aircraft without ozone converters. Airway irritation and reduced lung function. CS 25.832: Concentration < 0.25 ppm resp. 0.1 ppm.
• Pesticides	From aircraft “disinsection" with pesticides.
• **Engine Oil**	Fumes from hot engine oil may enter the cabin via the bleed air system.
• Hydraulic Fluids	Frequency of incidents is expected to be relatively low. Mild to severe health effects.
• Deicing Fluid	Hazardous substance. Skin sensitizing and irritant.
• Airborne Allergens	Exposure frequency is not known. Irritated eye and nose; sinusitis; acute increases of asthma; possible anaphylaxis.
• Nuisance Odors	Can be present on any flight.

Adapted from (NRC 2002)

Cabin Comfort and Cabin Air Quality – Health and Flight Safety Implications

Potential sources ... *of air contamination*	Potential impact
Engine start during push back	Exhaust gases (e.g., CO, CO_2, NO_X, fuel, particles)
Bleed air switch off during engine start	Short time increase of CO_2
Cabin cleaning in general **Interior cleaning**	VOC, e.g. alcohols, flavors (terpenes), aldehydes Residual of tetrachloroethene
No ozone converters installed	Ozone, particularly in cruise
De-icing fluids	1,2-Propanediol (major constituent) and various additives (e.g., dyes, thickener, antioxidants)
Aircraft traffic at the airport	Exhaust gases (e.g., CO, CO_2, NO_X, fuel, particles)
Car traffic at the airport	Exhaust gases (e.g., CO, CO_2, NO_X, gasoline, particles)
Passengers	Emission of CO_2, various VOCs, offensive smell
Restrooms	Smell, VOC from cleaning products
Furnishings	VOC/SVOC, particulate organic matter (POM), flame retardants e.g. organophosphates
Maintenance	Various VOCs, lubricants
Lubricants	Oil base stock, organophosphates, POM
Hydraulic fluids	e.g. Tributyl phosphate (TBP), triphenyl phosphate (TPP)
Engine oils	Tricresyl phosphate (TCP), trixylyl phosphate (TXP), Amines
In case of thermal degradation	VOCs, organic acids, aldehydes, CO, CO_2, potential unknown products

only considered here is: (Engine oils / In case of thermal degradation)

(EASA 2017a)

Health Effects: Occupational Health & Flight Safety

may be experienced soon after exposure or, possibly, years later:

- **Long-term heath effects**:
  - to passengers
  - to crew => **occupational health** (OH) **=> CS 25.831**
    usually related to
    Time-Weighted Average (TWA)
    Permissible Exposure Limits (PEL)

- **Immediate health effects**:
  - to passengers
  - to cabin crew
  - to cockpit crew => **flight safety implications** can lead to:
    injury or **death** of
    - passenger
    - crew **=> CS 25.1309**

(Eurofins 2017, EASA CS-25)

Occupational Health – Long Term Health Effects

EASA CS-25: CS 25.831 Ventilation

(a) Each passenger and crew compartment must be ventilated ... to enable crewmembers to perform their duties without undue discomfort or fatigue.

(b) Crew and passenger compartment air must be free from harmful or hazardous concentrations of gases or vapours. In meeting this requirement, the following apply: (1) Carbon monoxide concentrations in excess of one part in 20000 parts of air [50 ppm] are considered hazardous. For test purposes, any acceptable carbon monoxide detection method may be used. (2) Carbon dioxide concentration ...

"**EASA** is of the opinion ... only applicable for ... CO and CO2"
*Remark: EASA's interpretation of certification rules: The **cabin is allowed to be contaminated with other substances!***

"The **BFU** is of the opinion that 'harmful concentration' should be interpreted ... to mean that **health impairments** (including long-term) through contaminated cabin air should be **eliminated**."

"The **BFU** is of the opinion that a product [aircraft] which has received a type certificate by EASA should be designed in a way that **neither crew nor passengers** are harmed or **become chronically ill**."

(BFU 2014)

EASA
European Aviation Safety Agency

BFU

Bundesstelle für Flugunfalluntersuchung

German Federal Bureau of
Aircraft Accident Investigation

Flight Safety Implications – Immediate Health Effects

There have been **several** (much debated) **critical flight instances**,
but so far (luckily) **no death** (due to flight safety implicatons) and **no hull loss**.

Compare e.g. with the issue "Degraded Manual Flying Skills" (Flight International 2017)

Fatal in-flight loss of control accidents

Year	Operator	Type	Location	Fatalaties
2016	Egyptair	Airbus A320	Mediterranean Sea off Egypt	66
	Flydubai	Boeing 737-800	Rostov-on-Don, Russia	62
2014	AirAsia Indonesia	Airbus A320	Java Sea, Indonesia	162
2013	Swiftair	Boeing MD-83	Mali	116
	Tatarstan Air	Boeing 737-500	Kazan, Russia	50
	Asiana Airlines	Boeing 777	San Franciso, USA	2
2010	Afriqiyah Airways	Airbus A330-200	Tripoli, Libya	103
	Ethiopian Airlines	Boeing 737-800	Near Beirut, Lebanon	90
2009	Yemenia	Airbus A310-200	Comoros Islands	152
	Air France	Airbus A330-300	South Atlantic	228
	Caspian Airlines	Tupolev Tu-154	Iran	168
	Colgan Air	Bombardier Q400	Buffalo, New York, USA	49
2008	Aeroflot Nord	Boeing 737-500	Perm, Russia	88
2007	Adam Air	Boeing 737-400	Java Sea, Indonesia	102
2006	Armavia	Airbus A320-200	Sochi, Russia	113
2005	West Caribbean	Boeing MD-82	Venezuela	160
2004	Flash Airlines	Boeing 737-300	Sharm el-Sheikh, Egypt	148
2000	Gulf Air	Airbus A320-200	Bahrain	143
	Crossair	Saab 340	Near Zurich, Switzerland	10
Total				**2,012**

Source: FlightGlobal

From 2000 to 2017:

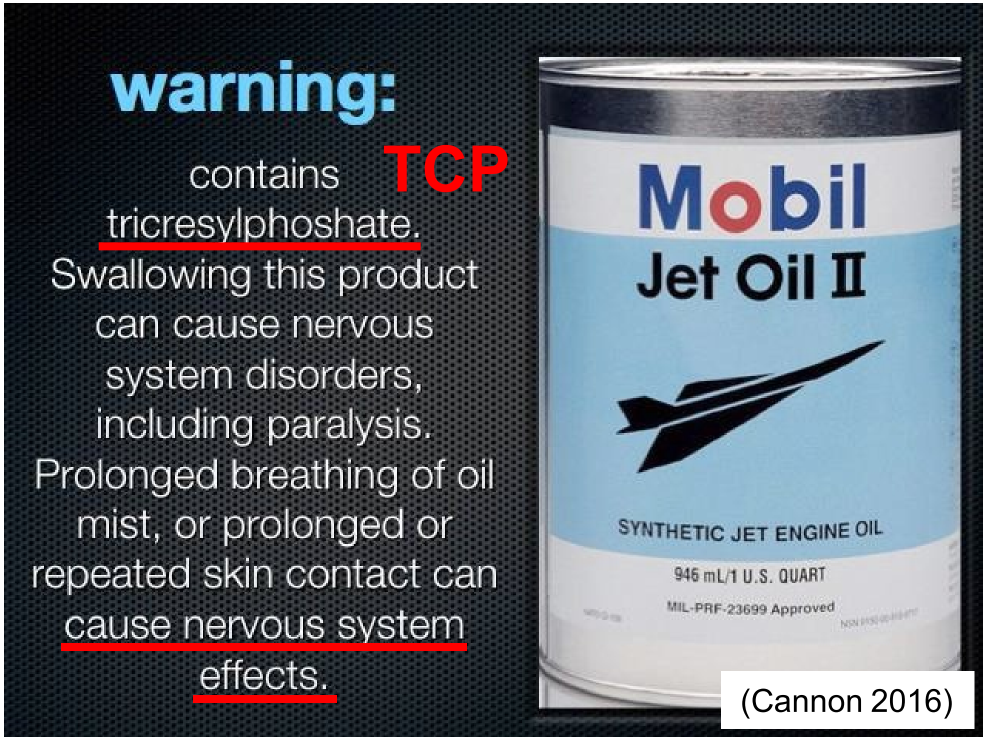
- 19 fatal accidents
- 2012 fatalaties

Remark:

There are certainly several issues in aviation of more pressing nature than "cabin air quality / contamination", however, the suffering of individuals (potentially / probably) due to cabin air contamination can not be ignored (may it just be for ethical reasons), because the underlying deficits in aircraft system design are a fact (see below) and need to be solved.

Jet Engine Oil

Jet Engine Oil



(Cannon 2016)

Judging Jet Engine Oil Based on Warnings Given by Manufacturer

ExxonMobil

Material Safety Data Sheet (MSDS)

FIRST AID MEASURES, INHALATION

Remove from further exposure [*in a fume event?*]... Use adequate respiratory protection [*not available for passengers!*]. If respiratory irritation, dizziness, nausea, or unconsciousness occurs, seek immediate medical assistance. If breathing has stopped, assist ventilation with a mechanical device or use mouth-to-mouth resuscitation.

(Exxon 2016c)

This warning was changed in 2004 (Michaelis 2012) to:

"This product is <u>not</u> expected to produce adverse <u>health effects</u> under normal conditions of use ... Product may decompose at elevated temperatures ... and give off irritating and/or harmful ... gases/vapours/fumes. Symptoms from acute exposure to these decomposition products in confined spaces [*aircraft cabin*] may include headache, nausea, eye, nose, and throat irritation."

(Exxon 2016c)

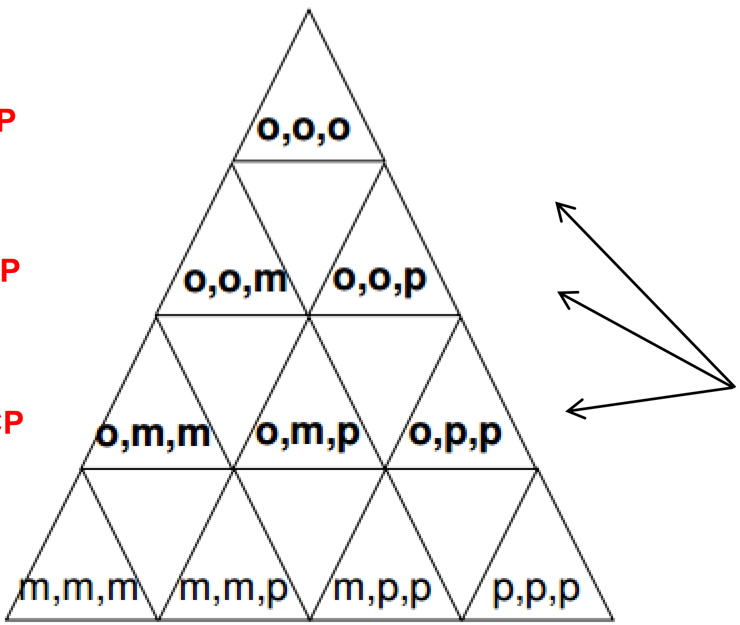
Jet Engine Oil

Tricresyl Phosphate (TCP)

TOCP

DOCP

MOCP

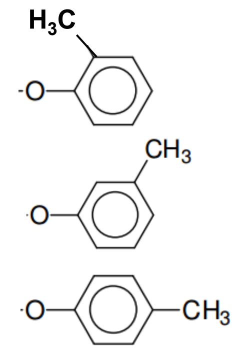


T = tri (3)
D = di (2)
M = mono (1)

o ortho-cresyl group

m meta-cresyl group

p para-cresyl group



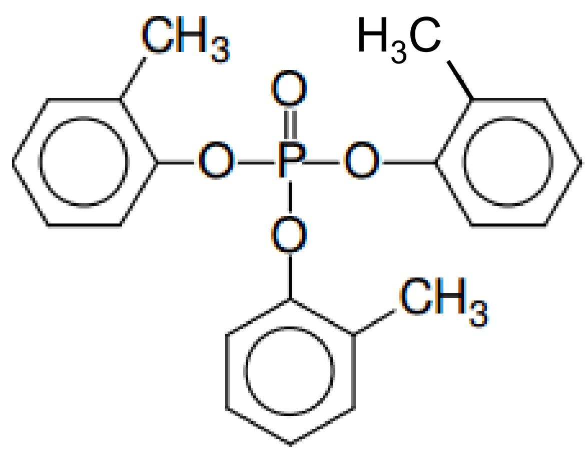
OC

MC

PC

ortho-cresyl group containing molecules are highlighted in **bold**, *they are the **toxic** isomers.*

TOCP:



(Winder 2001)

Jet Engine Oil

TCP Toxicity Basics

Winder 2001 / Henschler 1958

- The **10 isomers** that make up **TCP** are toxicologically different.
- The ortho containing isomers are toxic, without ortho isomers are not toxic (Henschler 1958).
- Most infamous and most studied: TOCP (tri-ortho-cresyl phosphate).
- Other ortho containing isomers in TCP are **more neurotoxic than TOCP**:
    - **DOCP** (di-ortho-cresyl phosphates): **5** times more neurotoxic (*TEF* = 5),
    - **MOCP** (mono-ortho-cresyl phosphates): **10** times more neurotoxic (*TEF* = 10).

- DOCP and MOCP are present in the engine oil in **higher concentration** than TOCP.

- Based on **concentration** (C_i in ppm) and **relative neurotoxicity** (toxic equivalency factor, *TEF*) for each isomer an *equivalent TOCP toxicity* (*TEQ*) can be calculated. The base unit of the equivalent TOCP toxicity is proposed to be that of 1 ppm (≈1mg/l) of TOCP in the oil. $TEQ = \sum C_i \cdot TEF_i$.

- Winder calculates this **equivalent TOCP toxicity**, considering the presents of all ortho isomers: TEQ for Mobil Jet Oil II: 30730
  (The TEQ of this oil would be less than 1 if only TOCP would be present and no other ortho isomers! Therefore, ignoring the DOCP and MOCP content of the oil yields highly inaccurate results.)
  TEQ for Mobil 291: 17606

Jet Engine Oil

TCP Toxicity Basics

Henschler 1958

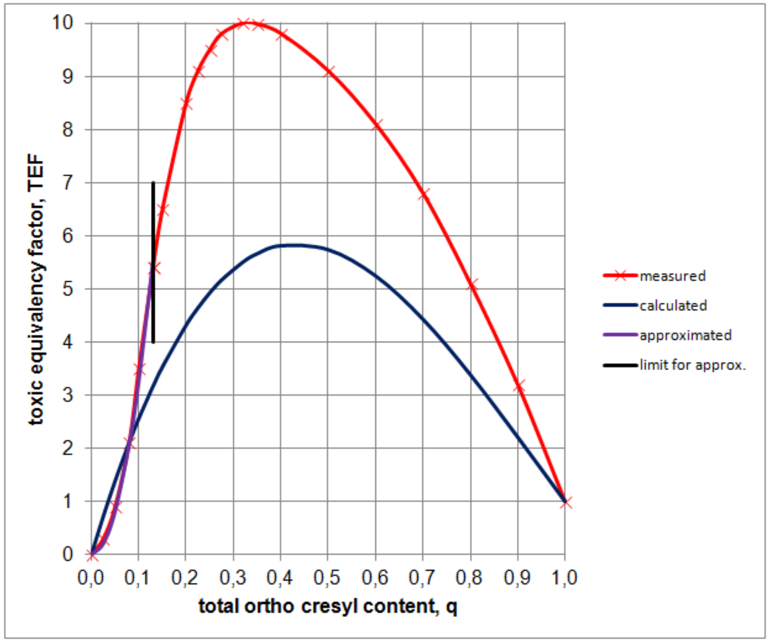
- TCP toxicity is found from animal poisoning with hens and cats.
- Results obtained from these test animals can be applied to humans (with caution).
- TOCP acts on the peripheral nerves and causes predominantly atonic peripheral paralysis.
- MOCP and DOCP act rather on the brain and on the spinal cord. This leads to spastic paralysis.
- If the content of TOCP, DOCP, and MOCP is known, calculation of TEQ is directly possible (see previous page).
- If only the total ortho cresyl (OC) content *q* in the TCP is known, the toxic eqivalency factor, *TEF* can be calulated based on a purely statistical distribution of the 10 isomers (as Henschler shows). It is easy to understand:
  - At 0% of OC neither of MOCP, DOCP, nor TOCP are present: *TEF* = 0
  - At 100 % of OC only TOCP would be present and *TEF* = 1 by definition.
- The theoretical formula (blue) is with *TEF*(TOCP) = 1:

$$TEF = 16q^3 - 45q^2 + 30q$$

- According to Henschler this curve needs to be adapted to fit his experimental results (red). An equation to fit this experimental curve would be (purpel):

$$TEF = 330q^2$$ valid for $q < 0{,}13$

and can be applied to typically low OC content.



Jet Engine Oil

Manufacturer Specified Jet Engine Oil Content and Toxicity

SAFETY DATA SHEET (MSDS) MOBIL JET OIL II (Exxon 2016c)
Synthetic Esters and Additives

Name	CAS#	Concentration*	GHS Hazard Codes
N-PHENYL-1-NAPHTHYLAMINE	90-30-2	1%	H302, H317, H400(M factor 1), H410(M factor 1)
ALKYLATED DIPHENYL AMINES	68411-46-1	1 - < 5%	H402, H412
TRICRESYL PHOSPHATE	1330-78-5	1 - < 3%	H361(F), H400(M factor 1), H410(M factor 1)

Exxon fails to specify the ortho Cresyl (OC) concentration of the oil. Exxon only uses the CAS# for the mixed isomers, as such hiding information.

H302: Harmful if swallowed
H317: May cause allergic skin reaction
H361(F): Suspected of damaging fertility
H400: Very toxic to aquatic life, H402: Harmful to aquatic life
H410: Very toxic to aquatic life with long lasting effects, H412: Harmful to aquatic life with long lasting effects

Remark:
According to the stated Health Hazards of Mobil Jet Oil II and the information in Michaelis 2010 (p. 67), the ortho content must be less than 0,2% in the oil (6,7% in the TCP) otherwie instead of the "harmful" declaration a "toxic" decalration would be mandatory. But with q = 6,7%, TEF = 1,47 and hence the TCP may still be more toxic than pure TOCP under the given hazard declaration!

Jet Engine Oil

Actual OCP Content of the TCP --- Isomerization

Ramsden 2013a
OC content in the TCP:
TCP Class 1: 30% (about 1930)
TCP Class 2: ?
TCP Class 3: 3% (about 1958, "modern TCP")
TCP Class 4: 0.3 % (since 1992, "conventional TCP")
TCP Class 5: ≈ 0,03 % (since 1997, "low-toxicity TCP")

TCP Class 6: 0 % **(since 2017**, "zero-OCP TCP") Remark / Introduction: Proposal for a new class definition

Ramsden 2013 / Imbert 1997
Another possibility is that **isomerization** of the **TCP** takes place within the engine during operation.

Megson 2016
... **temperatures of 400 °C**. These temperatures have the potential to alter the composition of the original oil and **create other toxic compounds**.

There is currently a large degree of **uncertainty as to what compounds are produced** and how toxic they are through **inhalation** in the vapour phase at high altitudes.

Jet Engine Oil

Actual OCP Content Measured

A comparison of fresh and used aircraft oil for the identification of toxic substances ...

(Megson 2016)	CAS #	[M+] m/z	Formula	Concentration in oil (%)					
				Fresh oil 1	Fresh oil 2	Fresh oil 3	Used oil 1	Used oil 2	Used oil 3
ooo-TCP	1330-78-5	368.118	$C_{21}H_{21}PO_4$						
oom-TCP		368.118	$C_{21}H_{21}PO_4$						
oop-TCP		368.118	$C_{21}H_{21}PO_4$						
omm-TCP		368.118	$C_{21}H_{21}PO_4$						
omp-TCP		368.118	$C_{21}H_{21}PO_4$						
mmm-TCP		368.118	$C_{21}H_{21}PO_4$	0.68	0.70	0.70	0.40	0.52	0.59
opp-TCP		368.118	$C_{21}H_{21}PO_4$						
mmp-TCP		368.118	$C_{21}H_{21}PO_4$	1.51	2.01	1.58	1.05	1.16	1.22
mpp-TCP		368.118	$C_{21}H_{21}PO_4$	1.21	1.42	1.39	0.78	0.97	0.87
ppp-TCP		368.118	$C_{21}H_{21}PO_4$	0.45	0.55	0.53	0.22	0.26	0.24
		Summation of TPC (%):		4.85	4.68	4.20	2.45	2.91	2.92

No tri-ortho cresyl phosphate **TOCP** isomers were detected.
No di-ortho cresyl phosphate **DOCP** isomers were detected.
No mono-ortho cresyl phosphate **MOCP** isomers were detected.

TCP Class 6: No OCP Content (2016)

Jet Engine Oil

EASA Study 2017: AVOIL (EASA 2017b)

AVOIL – Characterisation of the toxicity of aviation turbine engine oils after pyrolysis

"From the experimental work on detecting chemicals it is concluded that the commercial oils included in this study do contain TCP, however no tri-ortho cresyl phosphate [TOCP] isomers could be detected. *Remark: The content of DOCP and MOCP is not mentioned.*

A list of 127 compounds [VOC] was identified ...
(For hazard profile see Appendix 6 of EASA 2017b. See Remark 3 below.)

Analysis of the human sensitivity variability factor showed that the complete metabolic pathway and the contribution of inter individual variability in the metabolic enzymes is still largely unknown for the majority of industrial chemicals, ...

Based on the study on toxic effects of the oils after pyrolysis it was concluded that the current data indicate that neuroactive pyrolysis products are present, ...

... but that their concentration in the presence of an intact lung barrier is that low that it could not be appointed as a major concern for neuronal function."

Remarks / Questions:

1.) *No more TOCP. Good, but DOCP and MOCP were not in the focus. This could be misleading.*
2.) *What about people with deficits in their lung barrier functionality?*
3.) *"not ... a major concern for neuronal function" drawn too quick in view of the 127 compounds found, many with their individual hazards and possible interaction and their effect on humans.*

How much Oil Gets into the Cabin?

EASA Study 2017: AVOIL (EASA 2017b)

AVOIL – Characterisation of the toxicity of aviation turbine engine oils after pyrolysis

"a ... list of 127 compounds [VOC] was ... identified ... ". The hazard profile is given in Appendix 6:

Compound #	Name	CAS	Harmonized classification	Self-classification*
1	Diethyl Phthalate	84-66-2		NC
2	1-Nonene, 4,6,8-trimethyl-	54410-98-9		
3	2-Ethylhexyl salicylate	118-60-5		Skin Irrit. 2
4	Acetophenone	98-86-2	Acute Tox. 4 Eye Irrit. 2	
5	Benzaldehyde	100-52-7	Acute Tox. 4	
6	Benzene, 1,3-bis(1,1-dimethylethyl)-	1014-60-4	NR	NR
7	Heptane, 4-methyl-	589-53-7	Asp. Tox. 1 Skin Irrit. 2 STOT SE 3	
8	Nonanal	124-19-6		NC
9	2,4-Dimethyl-1-heptene	19549-87-2		Asp. Tox. 1
10	Decanal	112-31-2		Eye Irrit. 2
124	Isopropyl Myristate	110-27-0		NC
125	Tetradecanoic acid	544-63-8		NC
126	1-Pentene, 4-methyl-	691-37-2		Asp. Tox. 1 Or Skin Irrit. 2 Eye Irrit. 2 STOT SE 3
127	2-Cyclopenten-1-one	930-30-3		NC

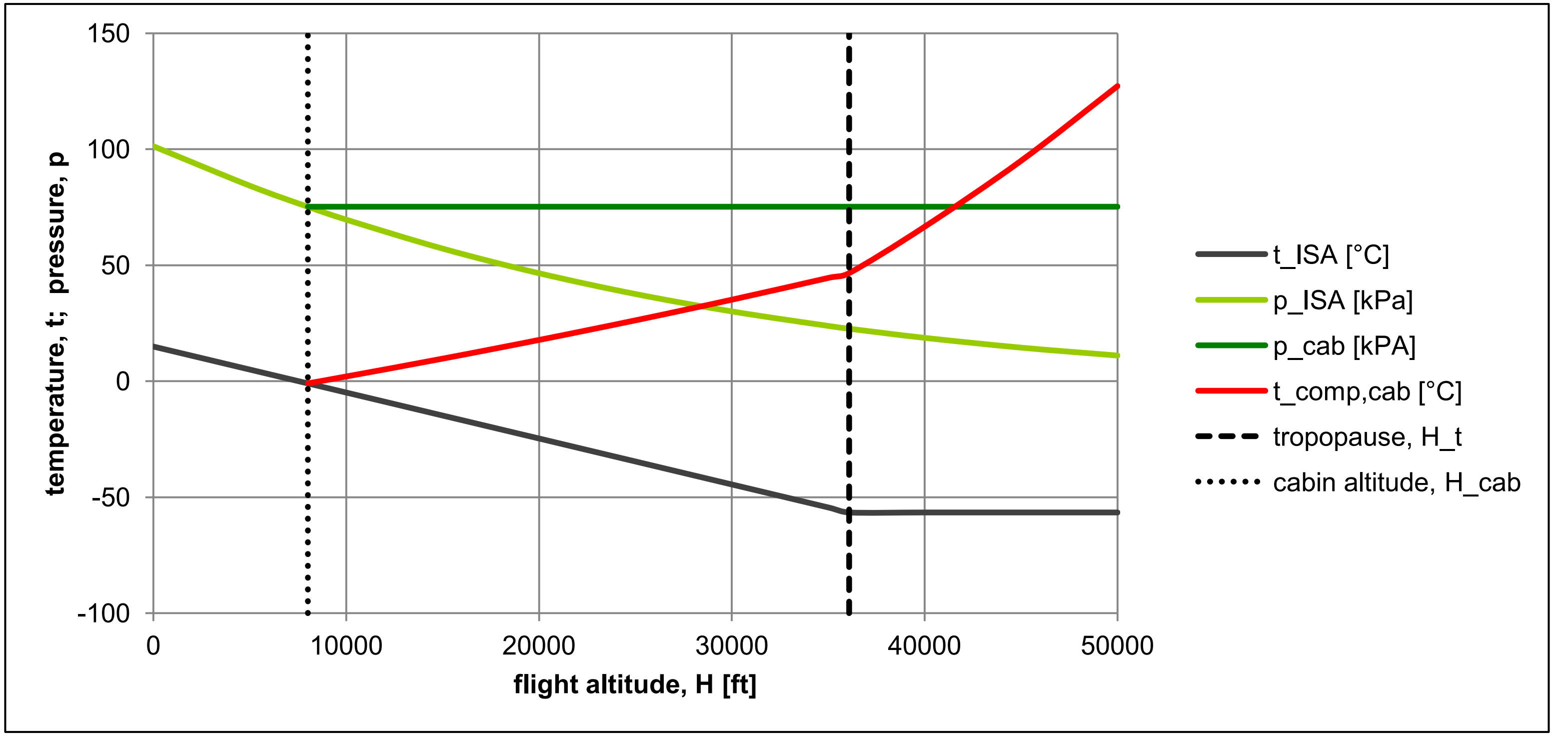
* according to the largest number of notifiers
NC = not classified for human health effects
NR = not registered under REACH

Air Conditioning Technology

Air Conditioning Technology

Air Conditioning Basics

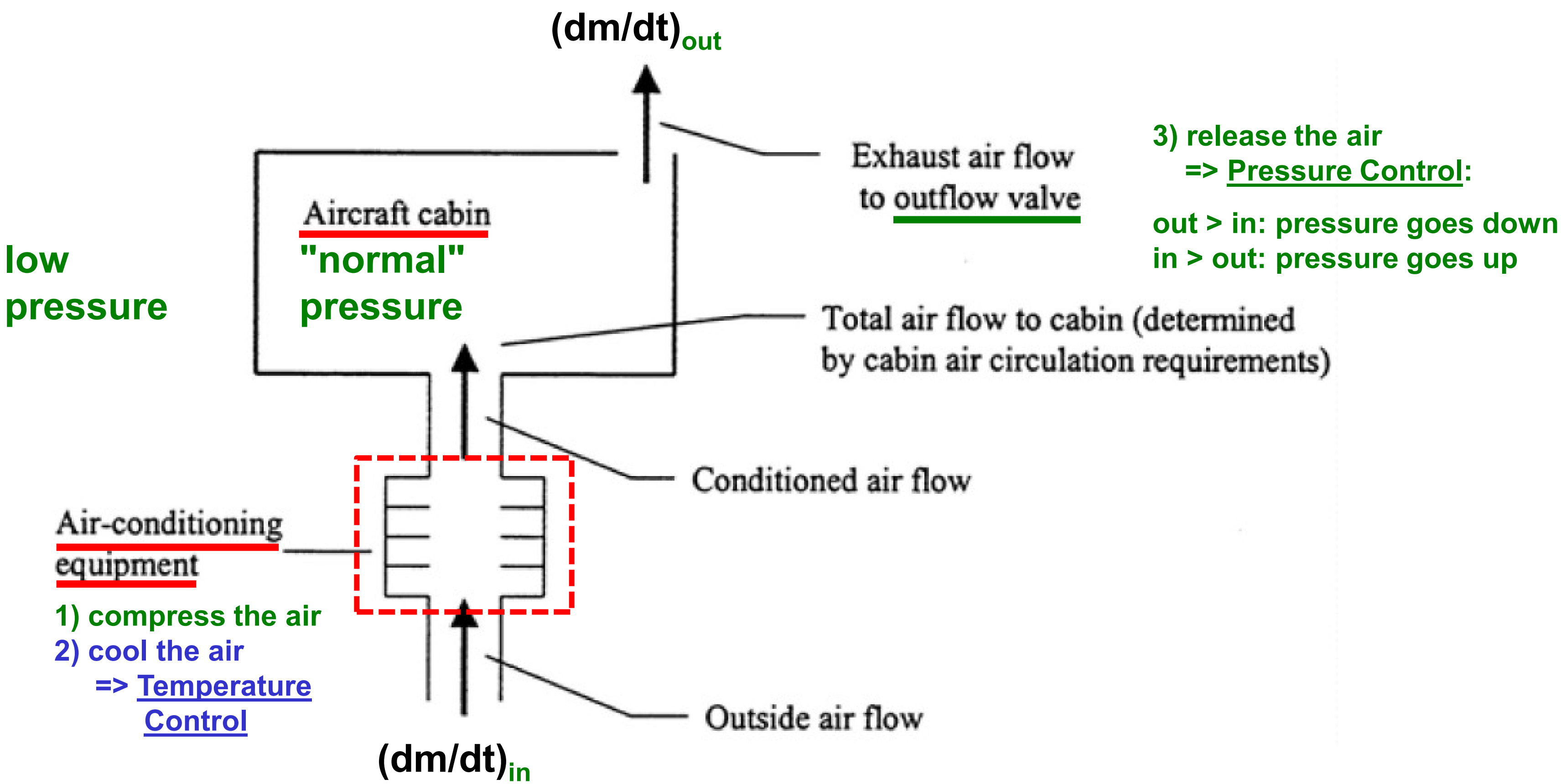
Increasing Temperature of Air due to Compression from Ambient to Cabin Pressure



1) compress the air => increasing temperature of air
2) cool the air

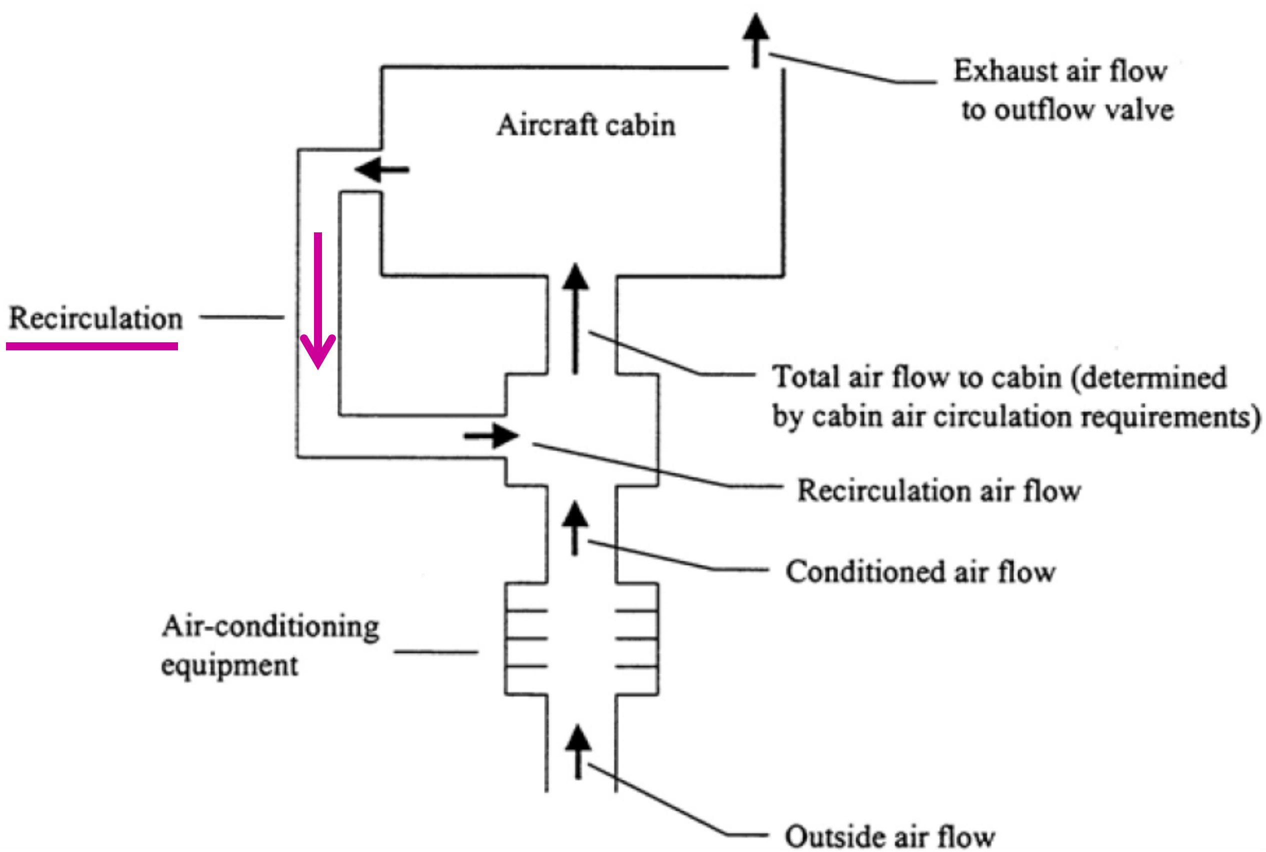
Air Conditioning Basics

Temperature Control, Pressure Control, Ventilation



Adapted from (NRC 2002)

Air Conditioning with Recirculation

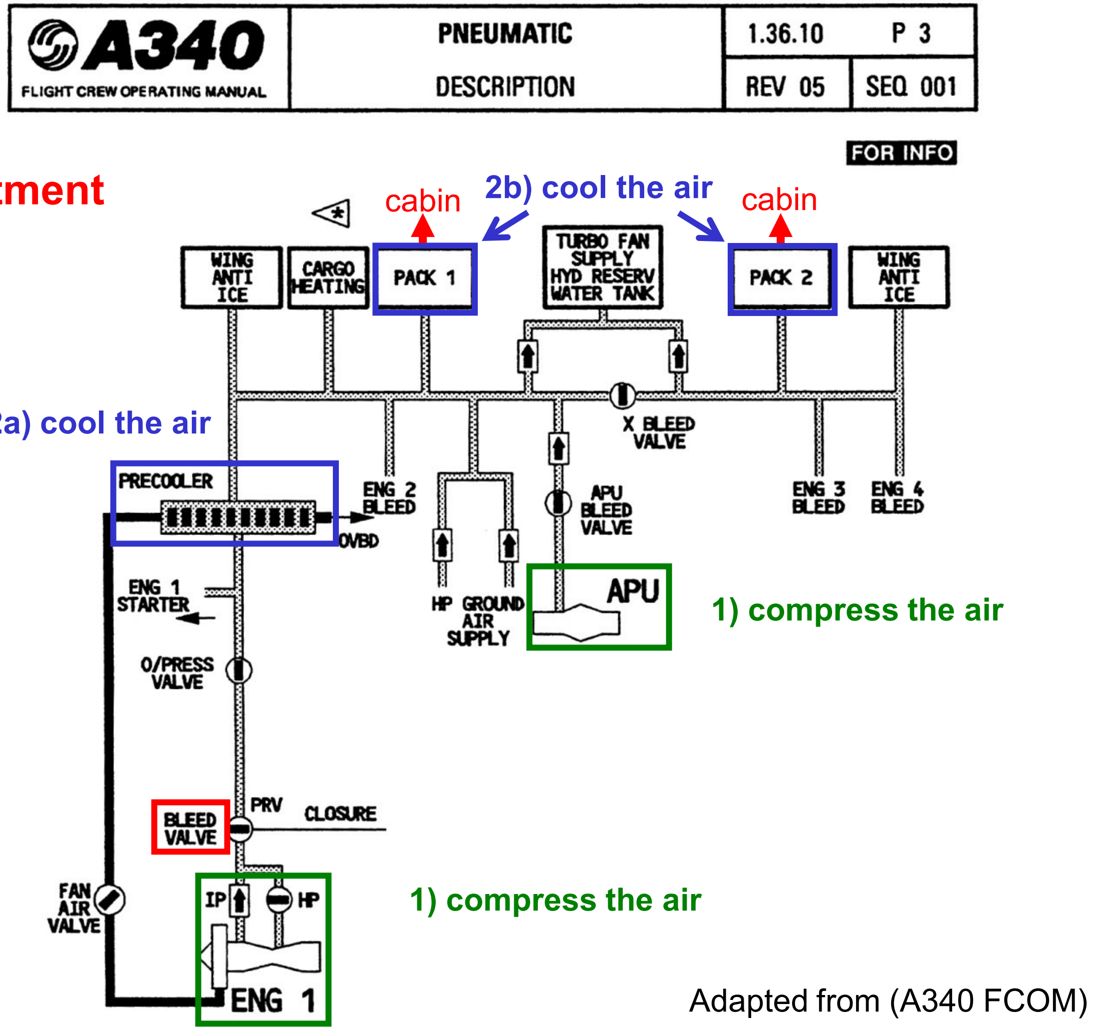


Adapted from (NRC 2002)

"Bleed Air" Generation and Treatment

compress and cool the air

"Bleed Air"
is "precious air" taken off the engine compressor – air which was initially intended to be used for the engine cycle

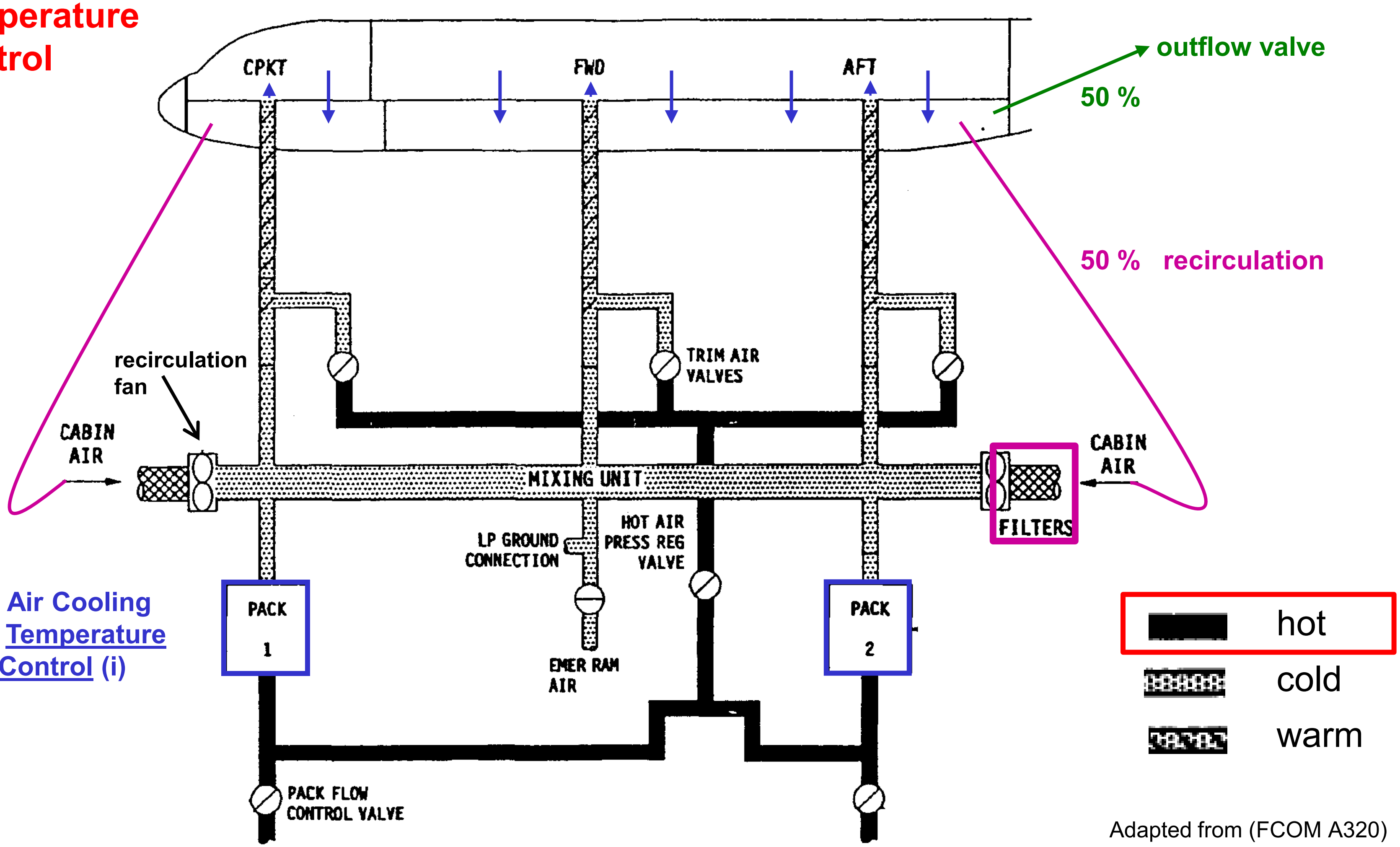


Adapted from (A340 FCOM)

Air Conditioning Technology

A320

Temperature Control

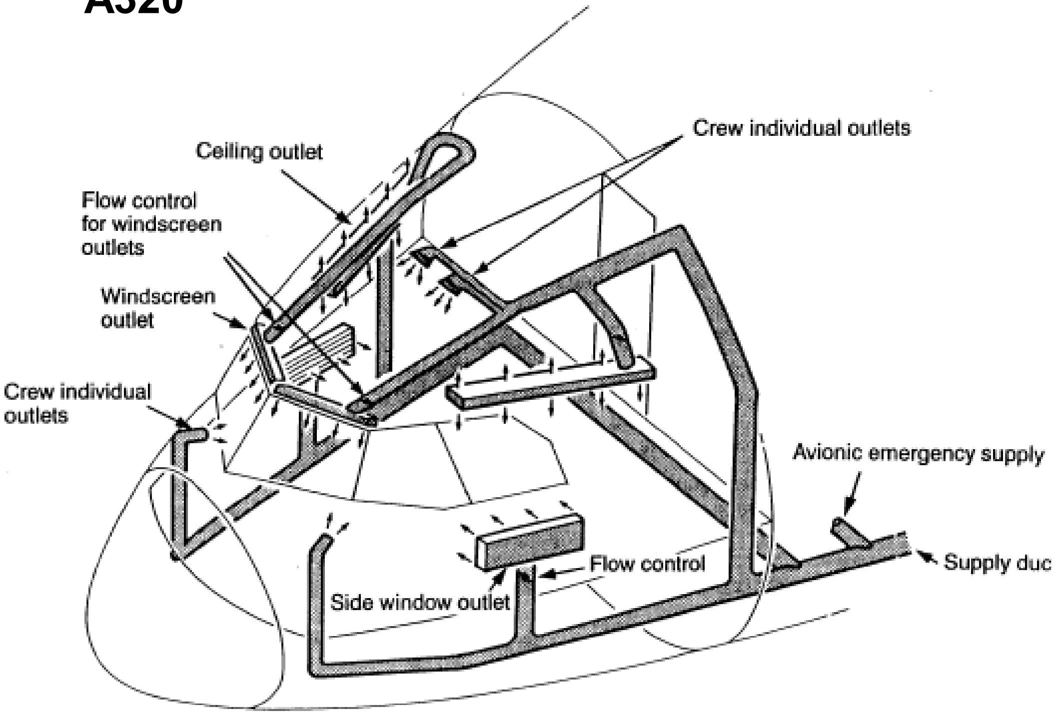


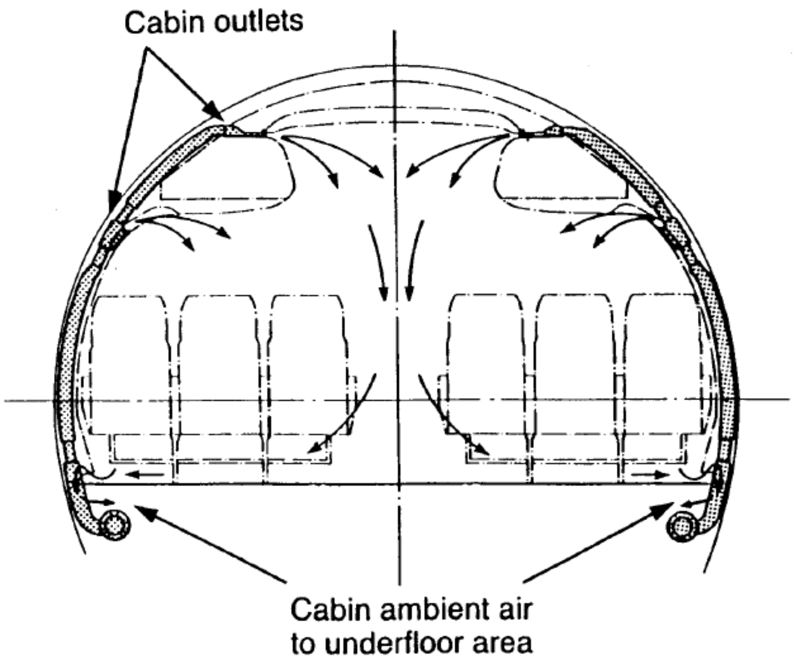
2b) Air Cooling
Temperature Control (i)

Adapted from (FCOM A320)

Cabin Air Distribution

A320

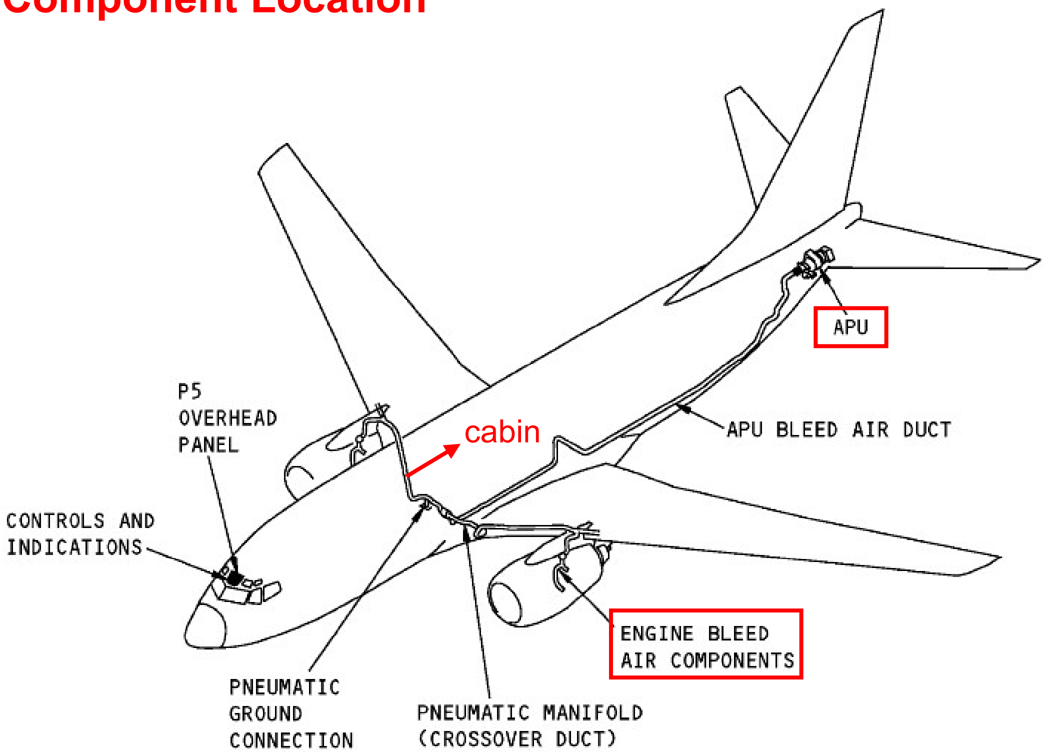




(A320 GENFAM)

BOEING 737-600/700/800/900 AIRCRAFT MAINTENANCE MANUAL

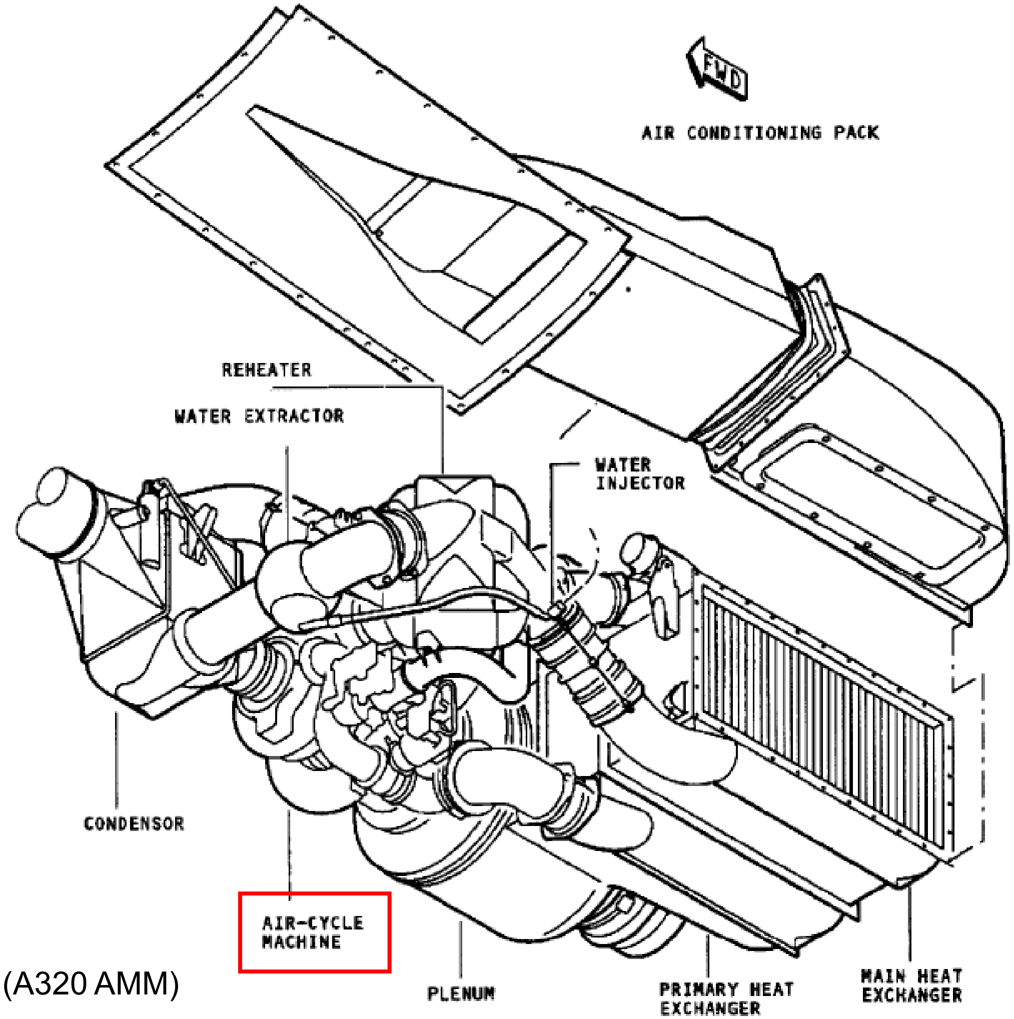
Major Component Location



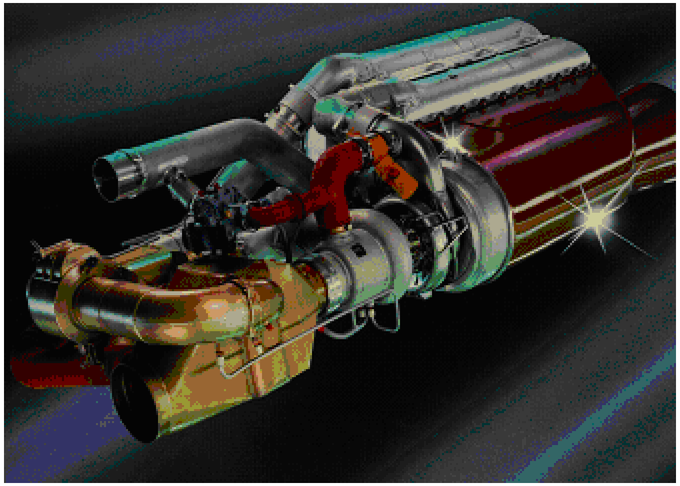
PNEUMATIC - COMPONENT LOCATIONS

(B737 AMM)

Air Conditioning Technology



(A320 AMM)

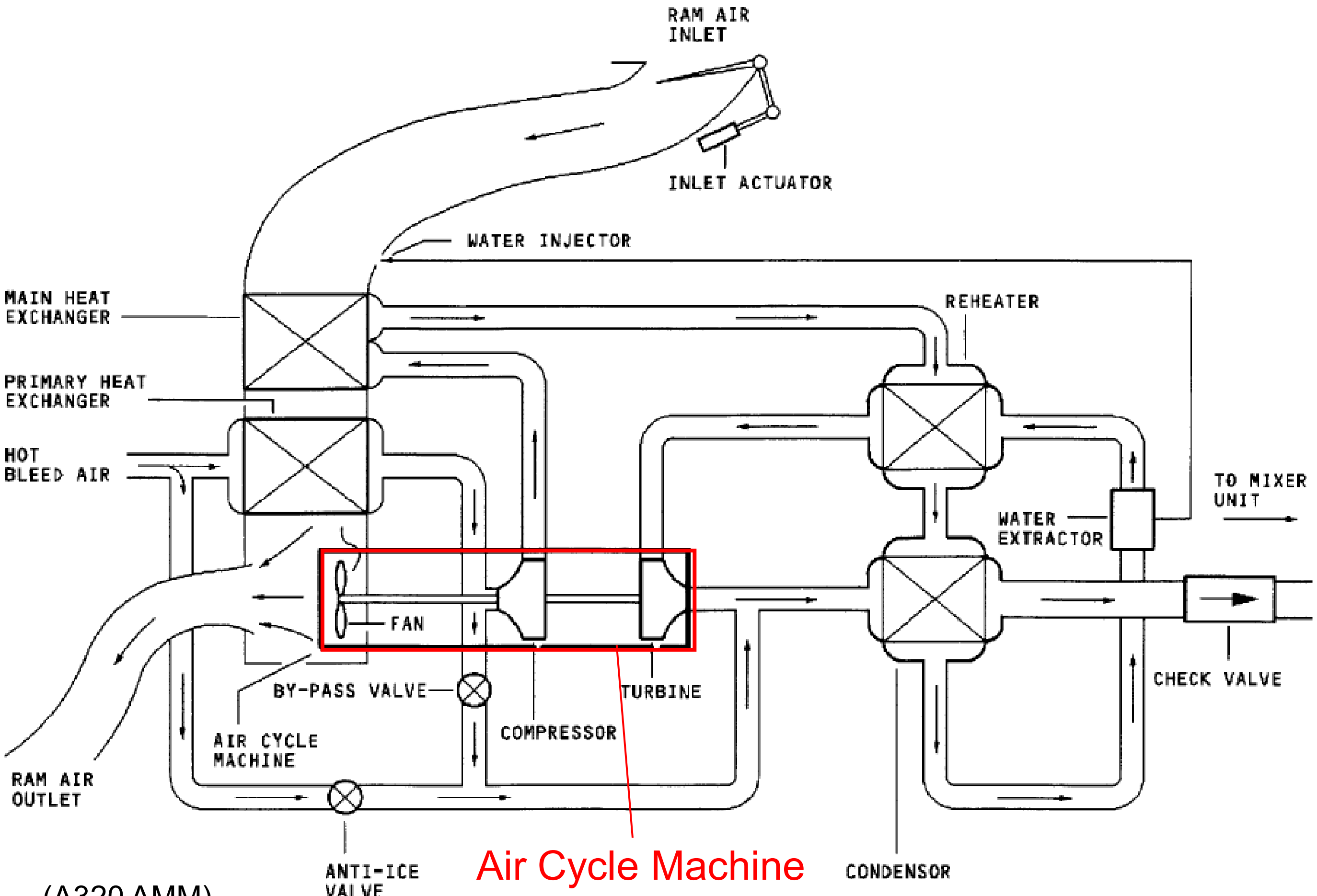


Liebherr Aerospace

Air Conditioning Pack (1/2)

A320

Air Conditioning Pack (2/2)



(A320 AMM)

- An Air Cycle Machine (ACM) is a high energy rotor device.
- An ACM may need some form of lubrication (=> oil)
- Lubrication needs will be much smaller than in aircraft engines or the APU.
- Use of air bearings is possible.

SAE about the Design of the Air Conditioning Pack

SAE ARP 85E: Air Conditioning Systems for Subsonic Airplanes

5.2.2.d:. Bearings:

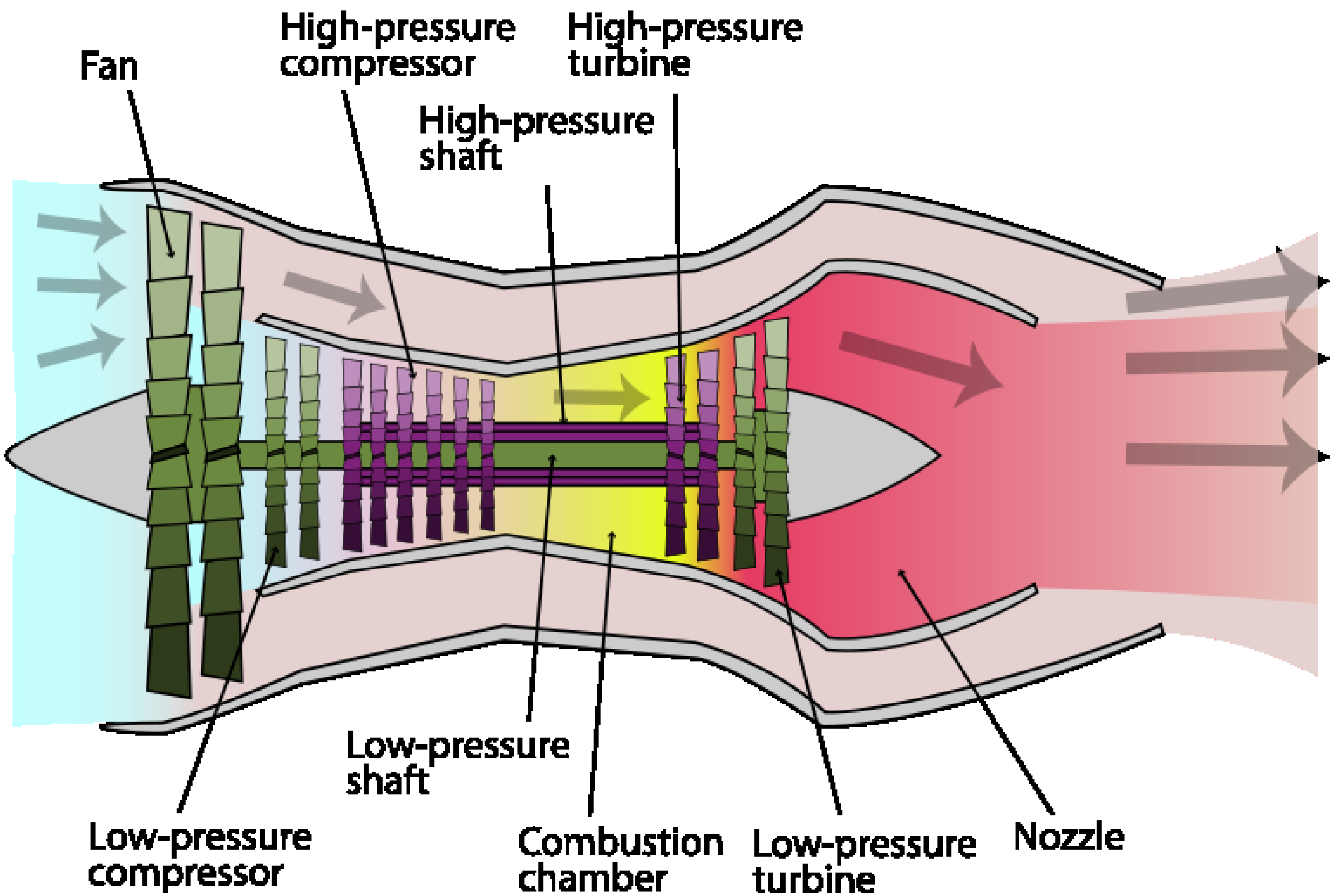
Air cycle machines typically use precision angular contact ball bearings or **air bearings**.

In either case, the bearing system should be self-contained, requiring no external oil supply or external pressurizing air source.

Jet Engine

Jet Engine

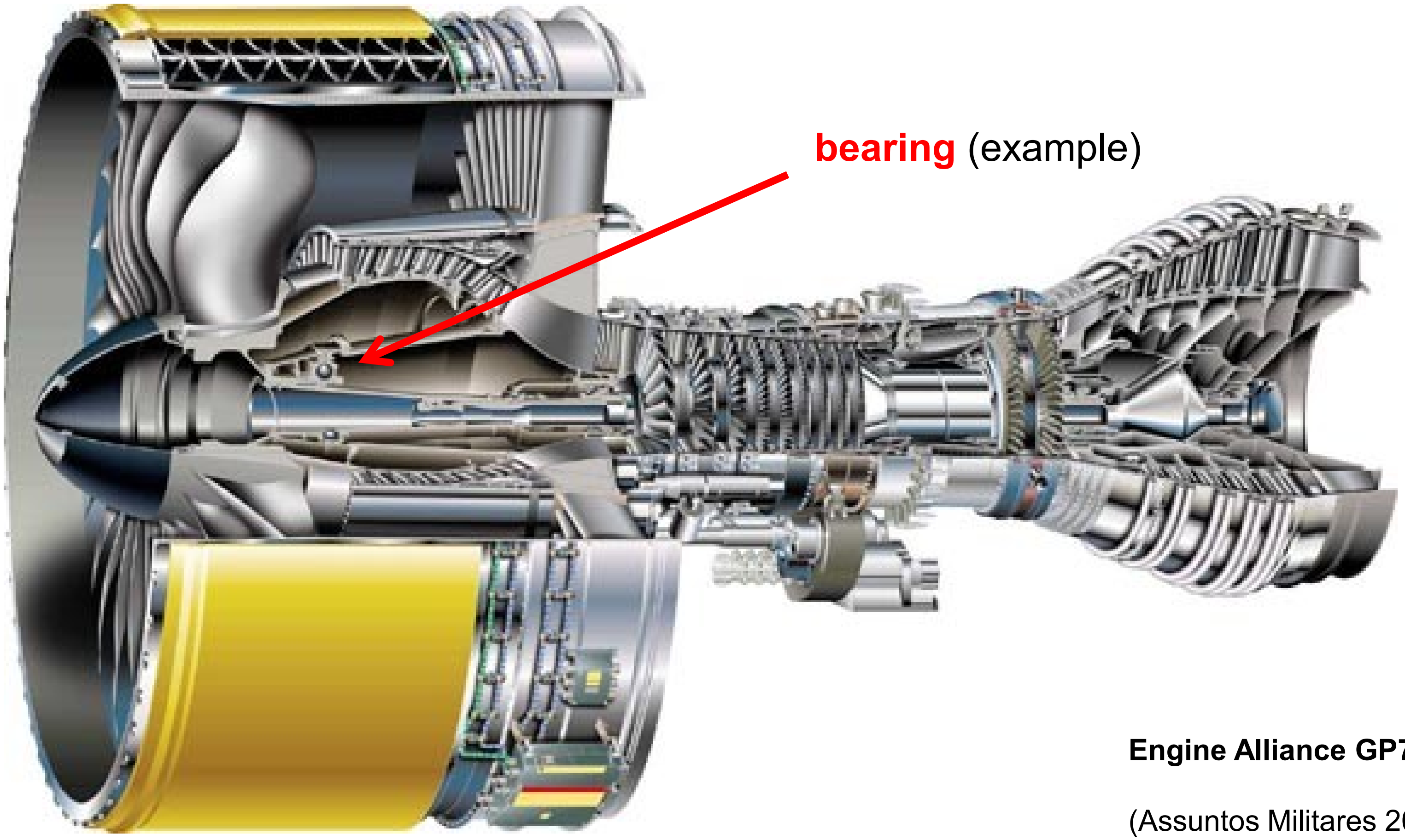
Engine Overview



(Wikipedia 2017a)

Jet Engine

Engine Overview



Engine Alliance GP7000

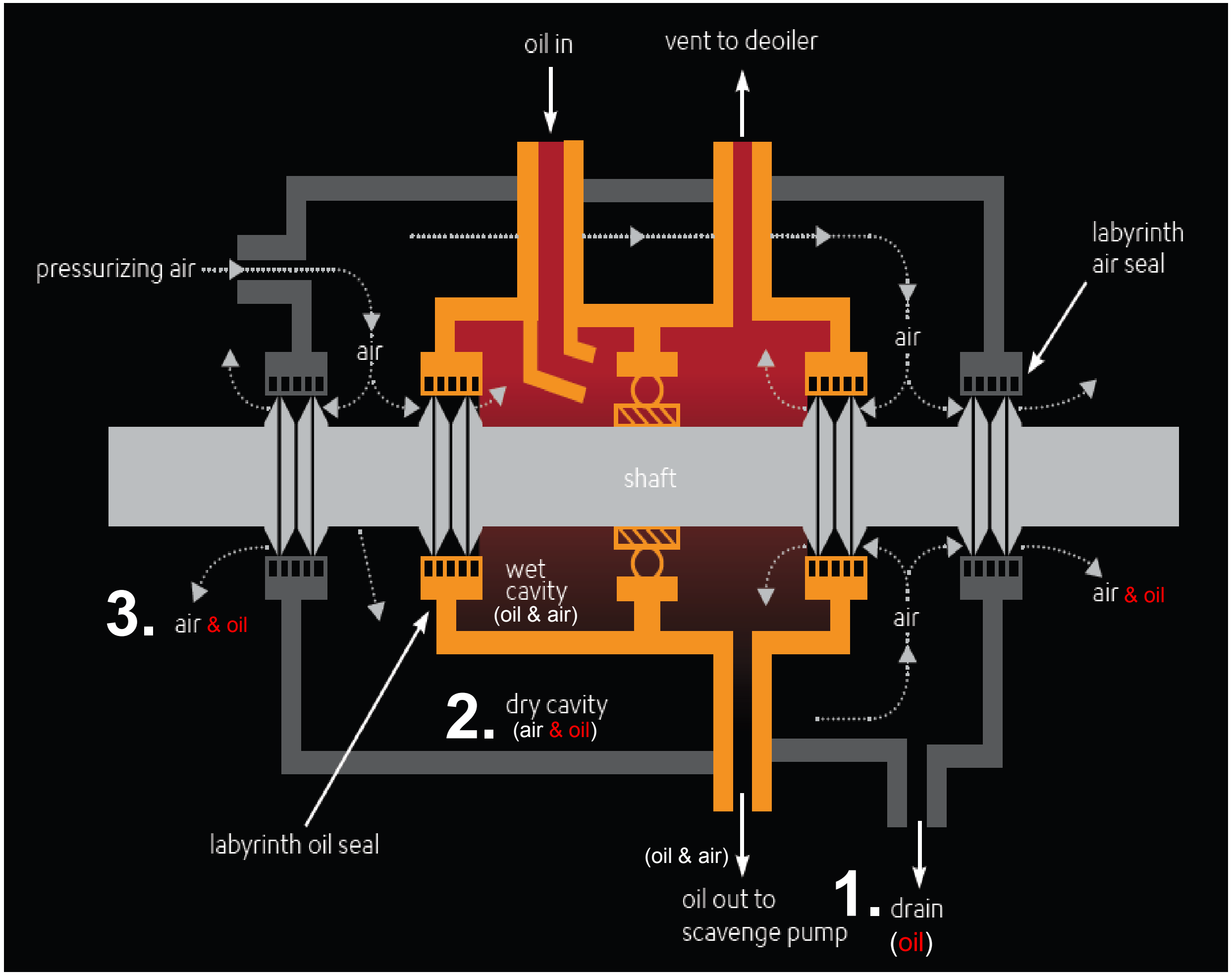
(Assuntos Militares 2013)

Jet Engine Bearing

(Exxon 2016b)

Jet Engine

Engine Air and Oil System



Normal operation of engine seals:

1. The "**drain**" discharges **oil**.
2. The "**dry cavity**" contains **oil**.
3. Air and **oil** leak from bearings **into** the **bleed air**.

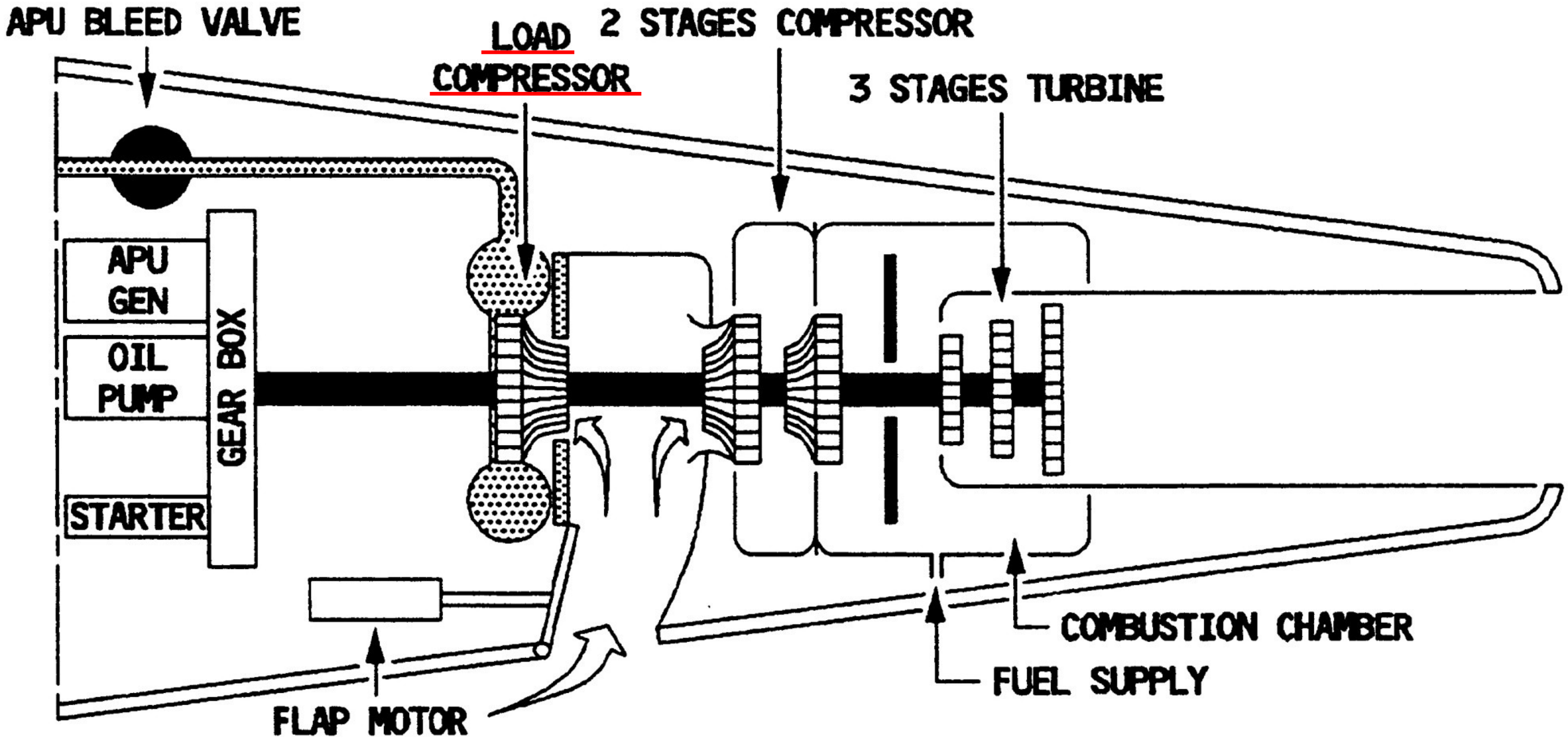
=> **Engines leak small amounts of oil by design!**

based on (Exxon 2016b)

Auxiliary Power Unit (APU)

Auxiliary Power Unit (APU)

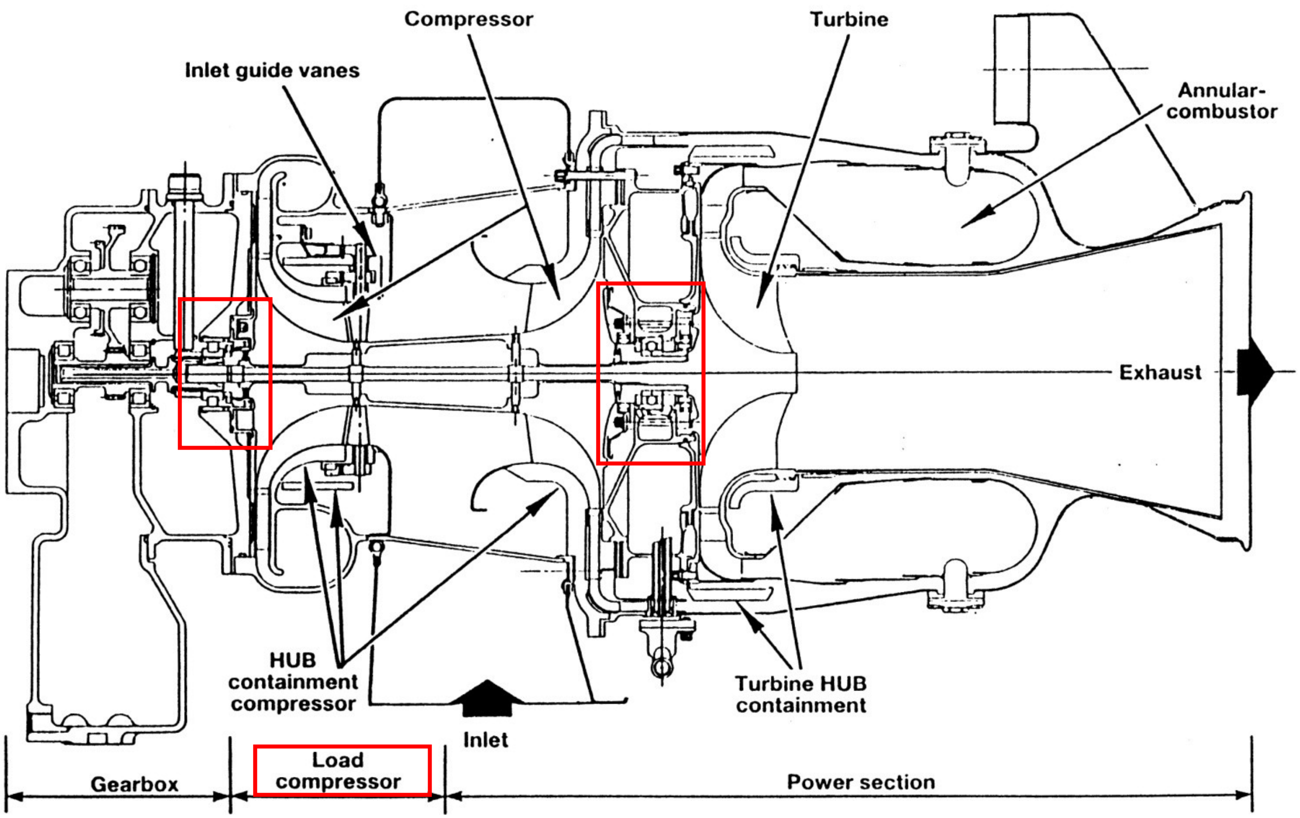
Overview



APU Description (A340 FCOM)

Auxiliary Power Unit (APU)

Bearings and Load Compressor



APU GTCP36-300

- An Auxiliary Power Unit (APU) is a gas turbine engine.
- An APU will need some form of lubrication (e.i. oil).
- Lubrication needs will be smaller than in aircraft engines, but the APU otherwise experiences the same problems with oil leakage as described for the engine.

(A320 GENFAM)

Engineering Design Principles

Engineering Design Principles for Air Conditioning from SAE

SAE ARP 1796: Engine Bleed Air Systems for Aircraft
(first edition 1987, A in 2007, B in 2012)

Bleed Air Quality: **Requirements** should be **imposed on the engine manufacturer** regarding the quality of the bleed air supplied to occupied compartments.

Under normal operating conditions:
The engine bleed air shall be **free of engine-generated objectionable** odors, irritants, and/or **toxic** of incapacitating foreign **materials**.

Following any type of engine … failure, the engine bleed air shall **not contain the above substances to a harmful degree**.

… or bleed air systems should incorporate a **bleed air cleaner**.

Engineering Design Principles for Air Conditioning from SAE

SAE AIR 1168-7: Aerospace Pressurization System Design
(first edition: 1991, A in 2011)
"Compressor bleed from turbine engines is attractive because of the mechanical simplicity of the system." However, "**oil contamination ... can occur in using compressor bleed air from the main engines**." "Popular opinion regarding the risk of obtaining contaminated air from the engine **may preclude its use for transport aircraft, regardless of other reasons**."

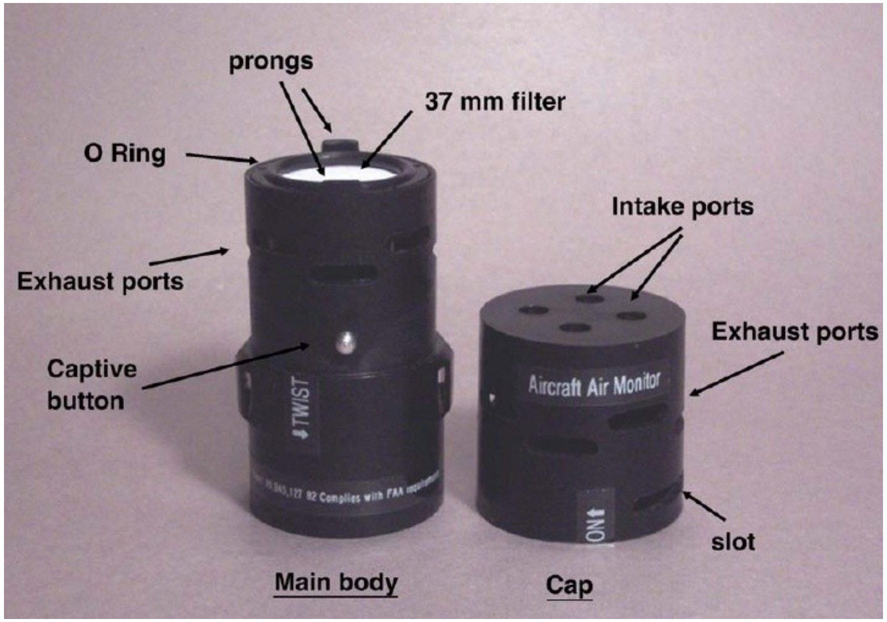
SAE AIR 1116: Fluid Properties
(first edition: 1992, A in 1999, B in 2013)
"**Until adequate toxicity data are available precautions** must be observed in handling any unfamiliar fluid."

This means:
It is not the task of passengers and crew to prove that engine oils and hydraulic fluids as used today are dangerous. Just on the contrary, **industry has to prove that fluids and equipment are safe <u>before</u> they intend to use them**, because standards have been agreed among engineers already long time ago, not to use bleed air on transport aircraft!

Sensors and Filters

Sensors and Filters

Air Sampler for Later Air Analysis



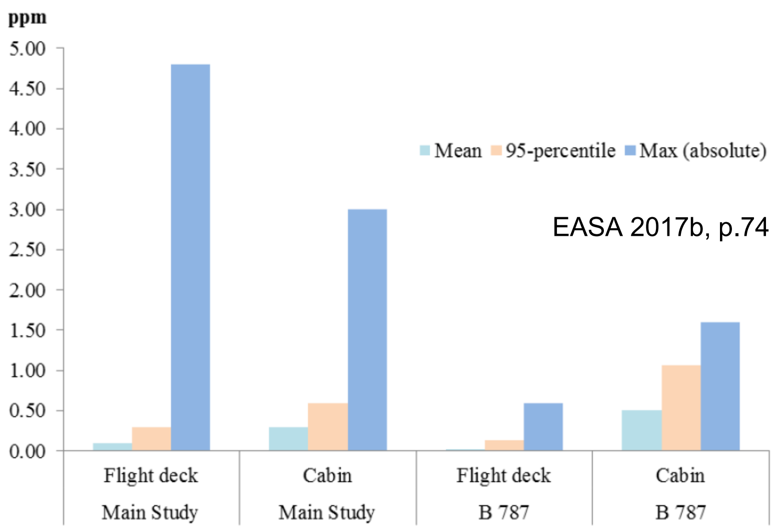
Prof. Van Netten invented this "VN-Sampler". It is not an in situ measurement device, but a means to collect the air in a fume event for later detailed analysis in a laboratory on the ground. The device is FAA approved.

(Van Netten 2008)

Sensors and Filters

Get Informed => Personal CO Detector. Get Protected in the Cabin => Breathing Mask

Normal CO Situation



- The **Carbon Monoxide** (CO) level in normal operation is much lower than the **limit of 50 ppm** (specified in CS 25.831). Failure cases did not occur during these measurements.
- We know much **CO is present in the cabin during a Fume Event. The elevated CO concentration indicates the severity of the event. Therefore, <u>crew</u> should carry their <u>personal CO detector</u> and and be informed and make decisions accordingly!**
- If smoke is present, checklists tell pilots to put on their oxygen mask. In such a case, cabin **crew should consider wearing a personal breathing mask protecting against nerve gas.**

Failure Case: Fume Event

US Airways Flight 432 Phoenix to Maui (2010)
(https://youtu.be/AZqeA32Em2s)

Get CO Detector and Breathing Mask

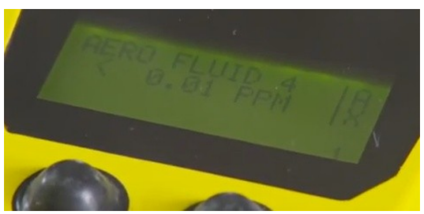
Cabin crew protection !

Sensors and Filters

Sensors to Detect TCP and VOC

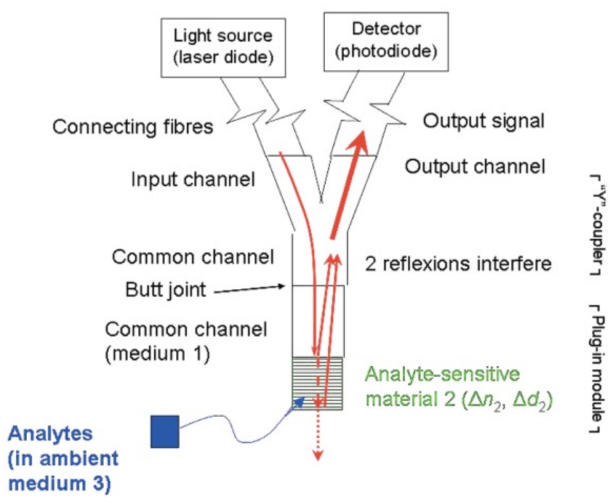
aerotracer (Airsense 2017)

- offered for sale.
- detects 15 substances: grease, liquid, gas: engine oils, de-icing fluids, hydraulic fluids, corrosion inhibitors, glue, heat transfer fluid, kerosene, ...
- power supply: 110 to 240 VAC; 30 W or rechargeable battery (operating time 4 hrs).
- electronics: graphical display, Mini SD Card.



VN Aerotoxic Detection Solutions (**VN-ADS**) (Aircraft Interiors 2017)

- prototypes are tested.
- Company claims to have the world's first real-time detector of poisonous compounds in aircraft cabins. (Aircraft Interiors 03/2017)
- Mono Fibre Optical Measuring Technology (MOMT) ... have demonstrated the capability to detect Tricrysel Phosphate (TCP) and other Volatile Organic Compounds (VOCs) and Semi Volatile Organic Compounds (SVOCs) in real time.



Measurement of hydrocarbon content (ppm- and ppb-level)

a) Measuring the (unaltered) bleed air from an APU at HAW Hamburg,

b) Checking the sensitivity of the equipment with pyrolyzed aviation fluids.

Gröger und Obst GmbH, 2014. The equipment is still too large (blue rack) for easy integration into the aircraft. See also: Reiss 2016. Smaller version on next page!

Sensors and Filters

Measurement of Hydrocarbon Content in Air
GO-MINI-ATC

Online analysis system for determination of the THC (Total Hydro Carbon) fraction of the air.

Power consumption max.:
350 W

Power supply:
230 V, 50 Hz

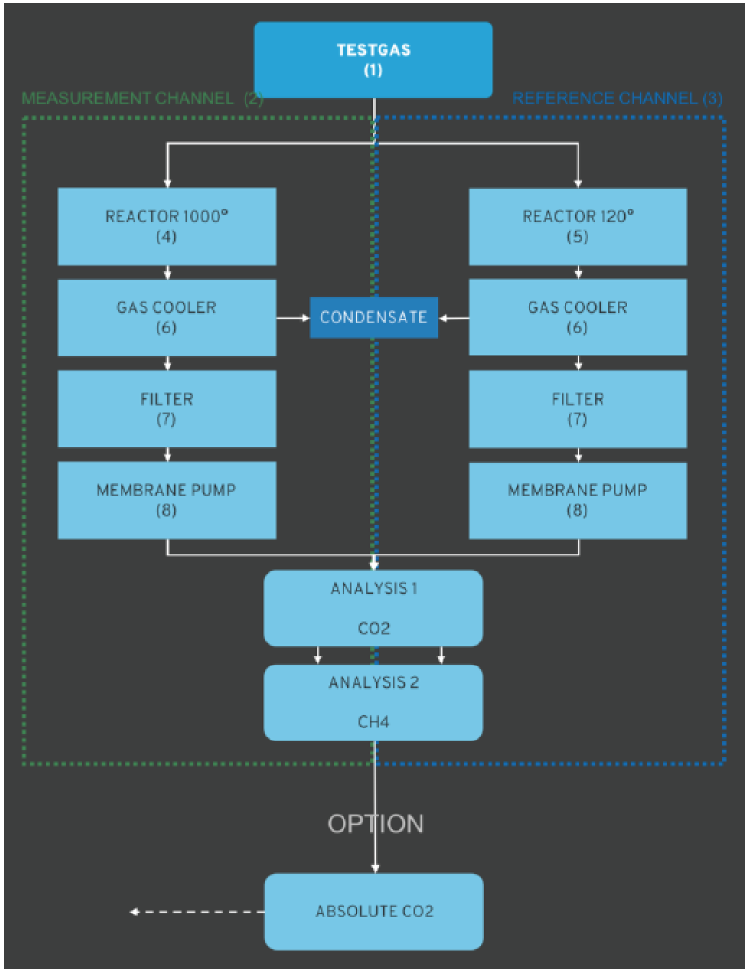
Dimensions (HxWxD) :
450mm x 440mm x 320mm

Weight:
30 kg

Operating temperature oxidation oven:
1.000 °C

Temperature rise time:
approx. 60 minutes

T90 time: 10 seconds



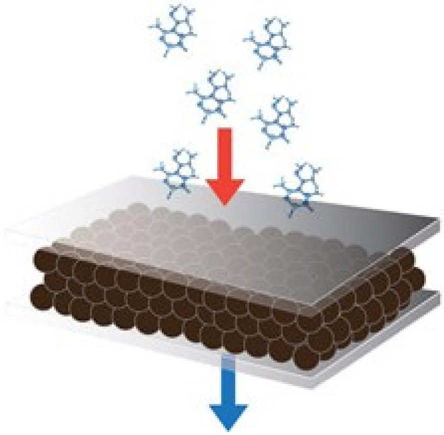
(Gröger 2017)

Sensors and Filters

Filters to Remove TCP and VOC

Pall has **several treetment** solutions for cabin air on offer:

- Carbon Filter
- Photo Catalytic Oxidization (with UV light)
- Catalytic Converters (oxidization). Location is possible:
  - upstream of the pack,
  - downstream of pack,
  - at recirculation filter
    (reduced efficiency compared to a filter in line with the pack – see next page)



Schematic of carbon Filter (Pall 2011)

Pall offers **Odour/VOC Removal Filters**

- The carbon adsorbent is effective at adsorbing volatile organic compounds (VOC). Test results have shown a removal efficiency of 65% ... 73% when challenged with TCPs in the gaseous phase. Carbon adsorbents have some effectiveness with ozone but not with carbon monoxide (CO). Removal of these compounds from the cabin air is by adsorption on to carbon based filters. (Pall 2011)

Application of carbon filters:

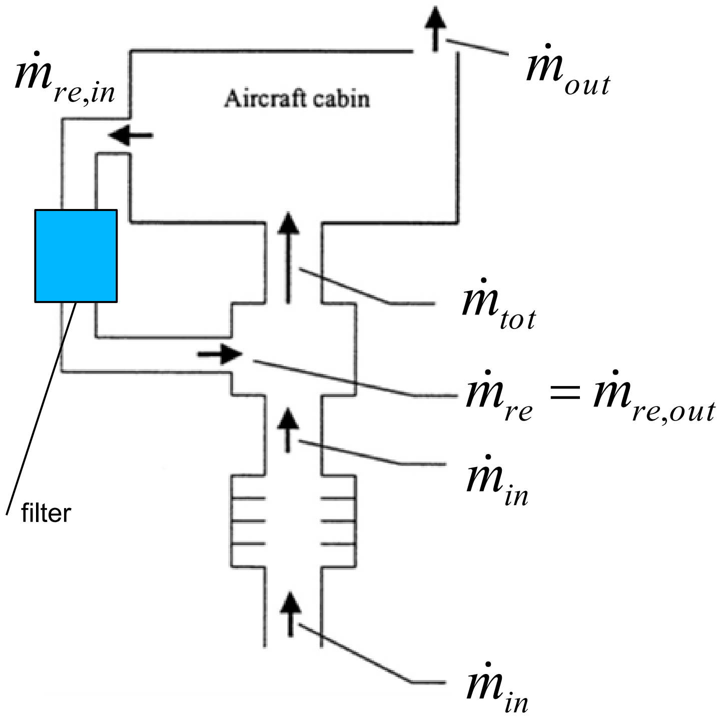
- 33 HEPA-Carbon filters have been added (so far) to A321 aircraft at Lufthansa Group. (Lufthansa 2017)
- Pall carbon filters are installed on the B757 cargo fleet of DHL. Carbon filters are installed in place of the air ducts leading to the cockpit. EASA issued an STC for the installation. (EASA 2010)

Sensors and Filters

Filter in the Recirculation Path

Example :

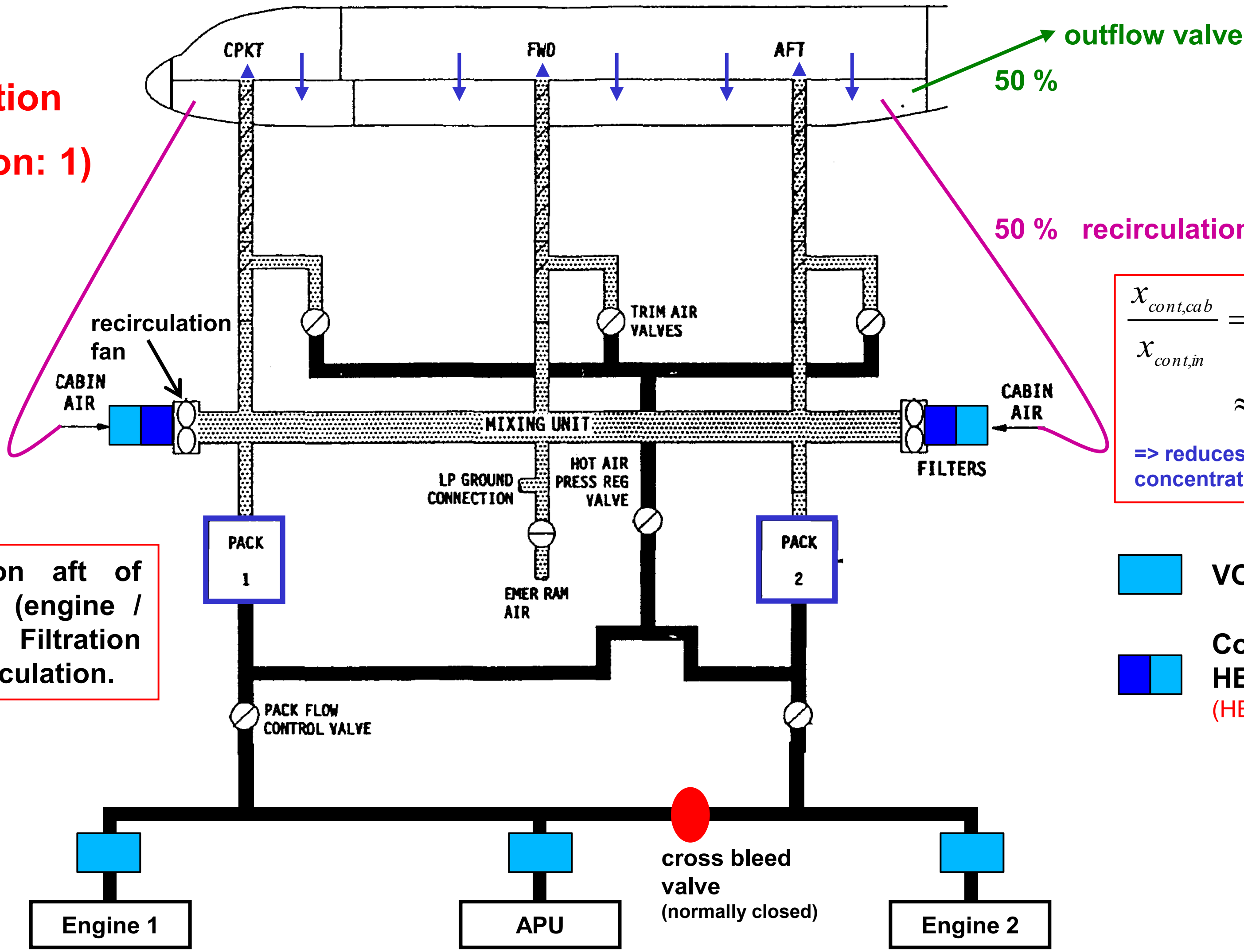
- The Pall carbon adsorbent is effective at adsorbing volatile organic compounds with a removal efficiency of 65% ... 73% when challenged with TCPs in the gaseous phase. (Pall 2011)
- The A320 has a recirculation rate of 50%.
- With a **filtration rate, x_{fil} = 0,7** and a **recirculation rate, x_{re} = 0,5**
- **=>** the filter **reduces the incoming concentration to 58,9%**.



Adapted from (NRC 2002)

Sensors and Filters

Full Filtration (Option: 1)



$$\frac{x_{cont,cab}}{x_{cont,in}} = (1 - x_{fil}) f_{recirc} \approx 0.3 \cdot 0.6 = 0.18$$

=> reduces incoming pollutant concentrations to ≈ 18%

Filtration aft of source (engine / APU). Filtration in recirculation.

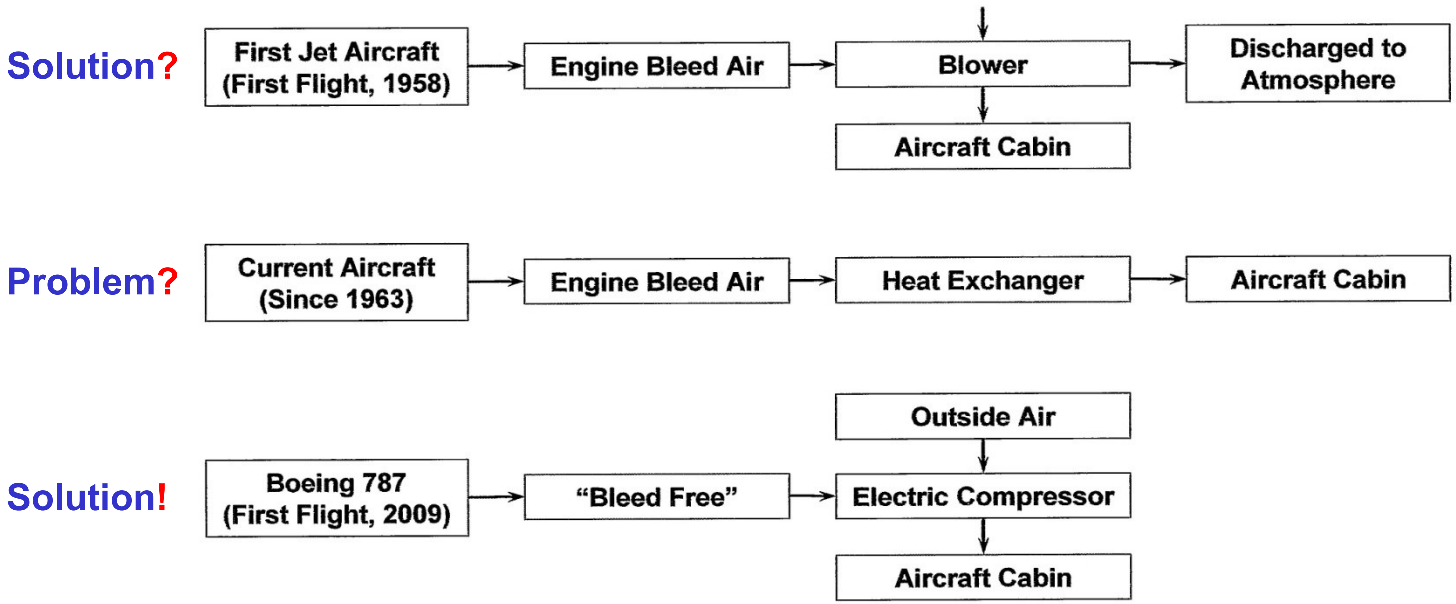
Technical Solutions

Technical Solutions

Cabin Pressurization Principles and Solutions

Overview

- **First Jet Aircraft** used a "blower" or "**turbocompressor**" (TC). The TC is the coupling of a turbine with a compressor. Bleed air from the engine compressor drives the TC turbine. The TCs compressor compresses outside air to meet the pressurization requirements of the cabin. The hot compressed air needs to be cooled. This can be done with a "vapor cycle system" (as known from the refrigerator).
- **Current Aircraft** make **use of bleed air directly**. It is compressed so much that it contains enough energy to also drive the pack that cool the bleed air down to temperatures considerably less than 0°C.
- The **Boeing 787** uses electrical power to drive an electric motor to drive a compressor. The **energy is extracted from the engine by means of shaft power driving a generator**. No bleed air is used. The engine is "Bleed Free".



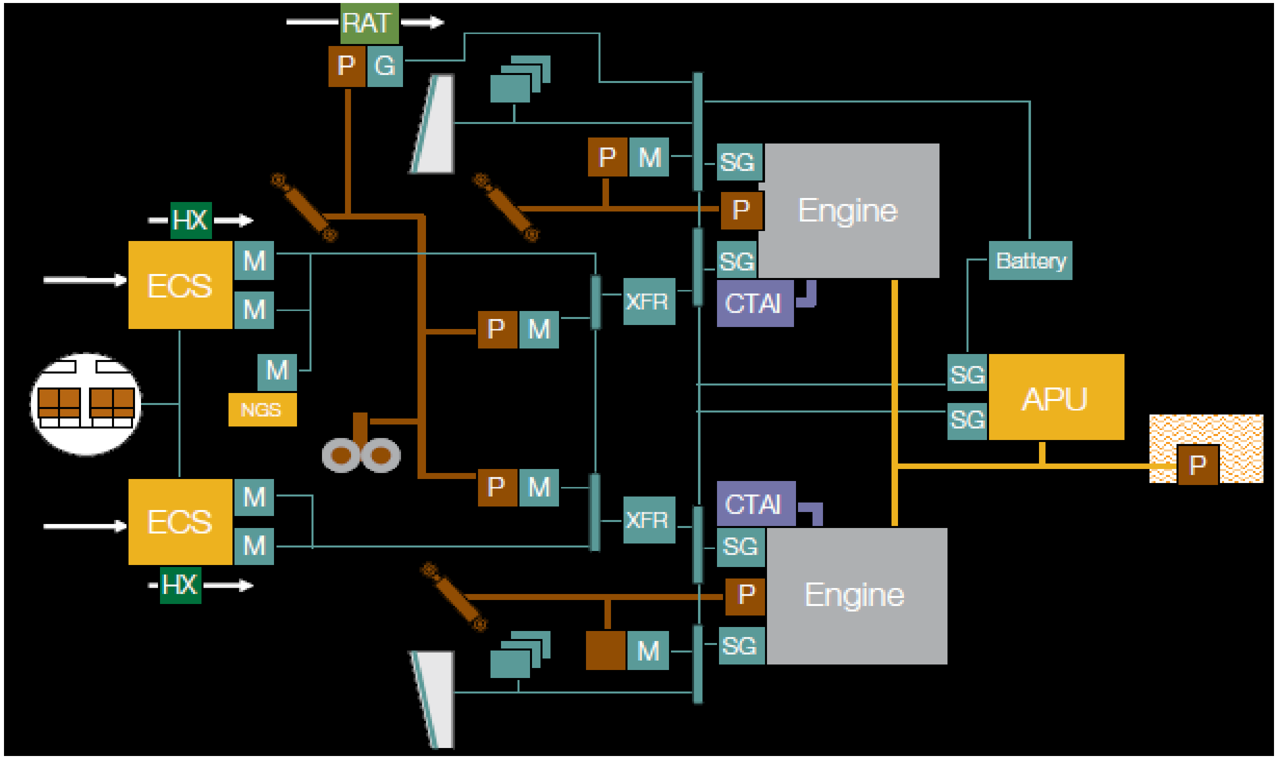
(Michaelis 2010)

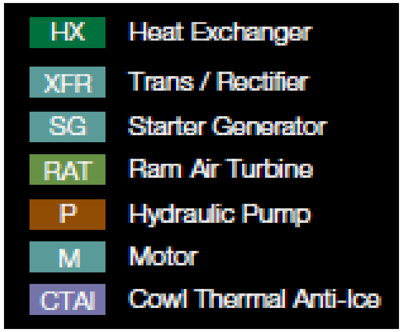
Technical Solutions

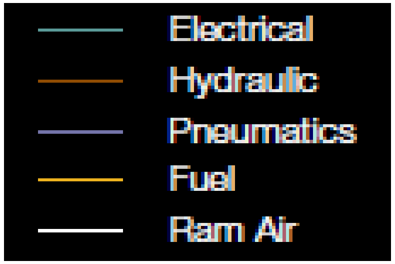
Electrical (Bleed Free) Cabin Air Supply

Solution B787!

Boeing 2007





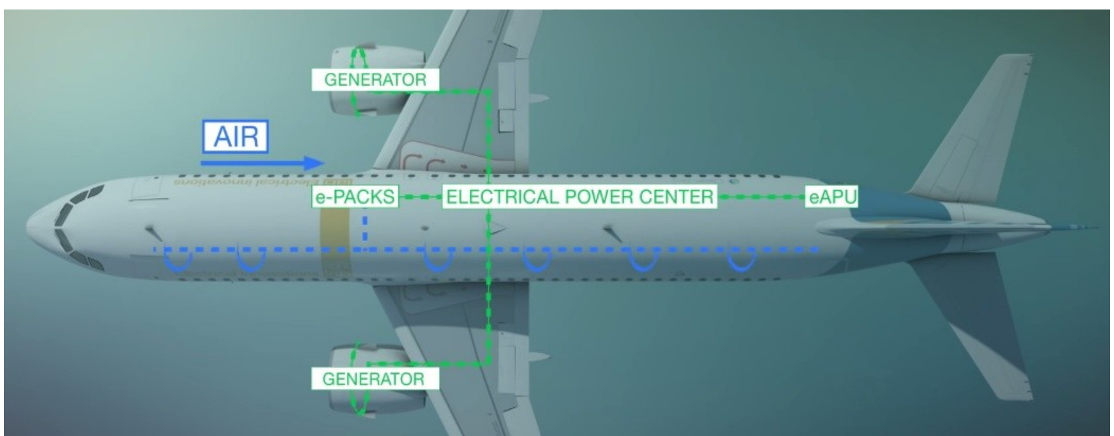


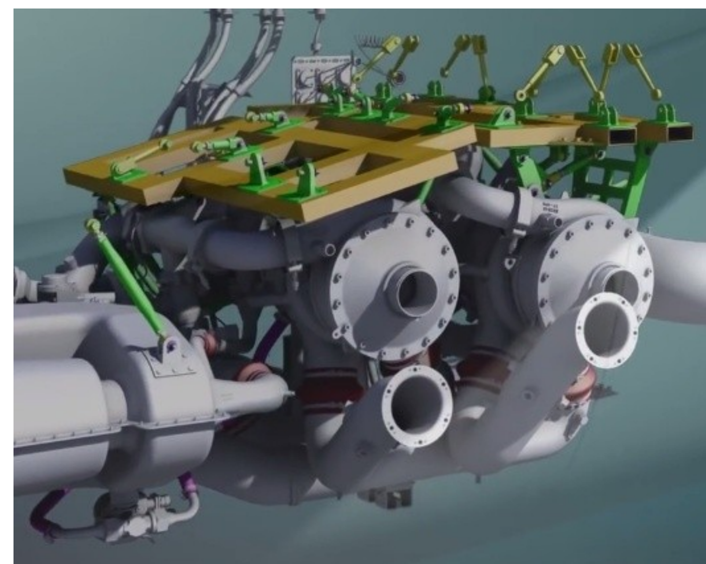
The "Pack" of the B787's Environmental Control System (ECS) is powered by electric motors (M) to compress ambient air up to cabin pressure and to push the air through the heat exchangers (HX) for cooling. The power for the electric motors is produced by generators (SG) connected to the aircraft's engine and APU. After compression and cooling the air is delivered to the cabin.

Technical Solutions

More Electric A320?

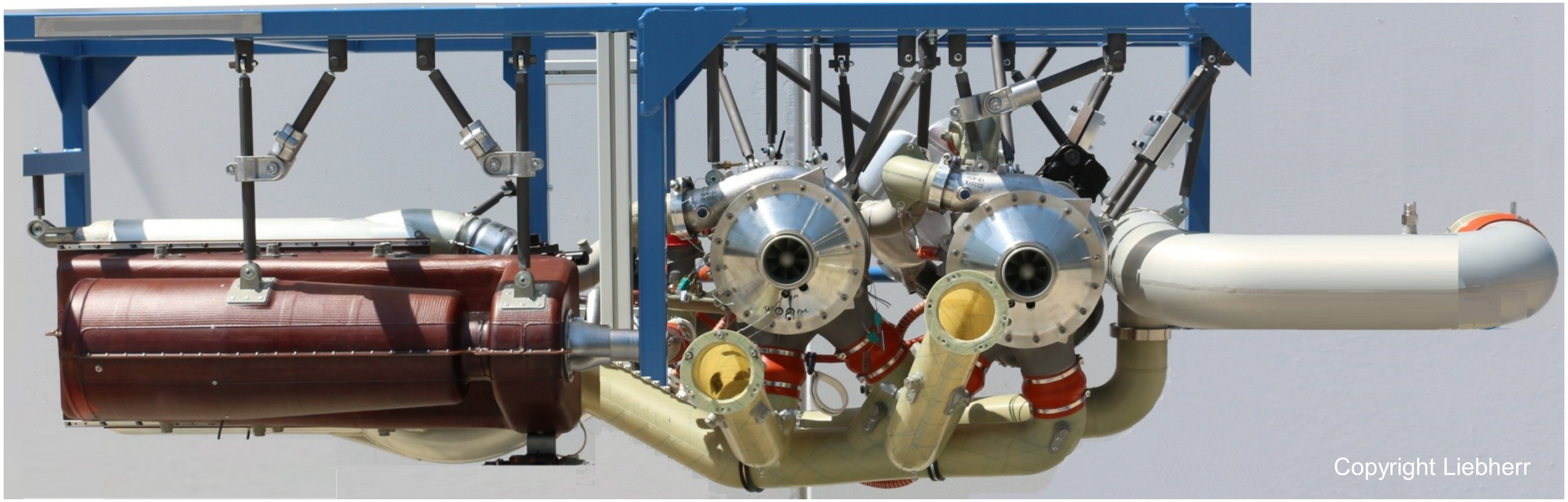
Electrical innovations
flightlab





Technical Solutions

More Electric A320 with Electrical (Bleed Free) Cabin Air Supply?



The Electrical Environmental Control System (E-ECS) was developed by Liebherr-Aerospace Toulouse SAS, Toulouse (France), Liebherr's center for air management systems. The E-ECS is equipped with a new type of motorized turbo compressor (50 kW) which enables to use directly external air (bleed less) for air conditioning. The power electronics ensure the speed control of the motorized turbo compressor and offer synergy capabilities with other electrical loads to optimize the overall electrical power consumption on board the aircraft. The interaction between air intake and the turbo-compressors and the performance of the system in all operating conditions was tested in a flight test campaign with Airbus A320-Prototyp MSN001 from June 3 to June 24, 2016. E-ECS will also contribute to fuel burn reduction.

(Liebherr 2016)

Summary

- There are many reasons for aircraft cabin air contamination. Important:
  engine oil, hydraulic fluid, anti-icing fluid – **chemically altered** at high temperatures
  (=> different chemicals than expected, causing different symptoms)

- **Engine seals leak a small amount of oil by design =>**
  continuous low dose contamination in (almost) **all jet aircraft**

- **Fume Events** could be called better **Cabin Air Contamination Events (CACE) =>**
  occasional high dose contamination

- Crew should not use their nose as sensor. Instead: **use low-cost CO sensors**

- **Demand technical changes: filter** for retrofit and
  bleed-free architecture for newly designed aircraft

Contact

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http://www.ProfScholz.de

http://CabinAir.ProfScholz.de

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